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Research Triangle Park, NC

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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1. SUMMARY

1.1 REGULATORY OPTIONS

The Administrator considered five regulatory options for controlling continuous process benzene emissions from process vents in the ethylbenzene/styrene (EB/S) industry: (1) Do not set a standard, assuming benzene emissions from process vents are controlled adequately to protect public health; (2) Regulatory Option A -- Require that continuous benzene emissions be reduced by 85 percent, based on the use of scrubbers and condensers; (3) Regulatory Option B -- Require that continuous benzene emissions be reduced by 94 percent, based on the use of a flare system coupled to scrubbers and condensers; (4) Regulatory Option C -- Require that continuous benzene emissions be reduced by 99 percent, based on the use of a boiler*; and (5) Regulatory Option D -- Require that continuous benzene emissions be reduced by 100 percent, based on plant closure and substitutes for styrene. Because there are no technological reasons to consider different or alternative controls for new or existing sources, these regulatory options apply to all EB/S plants. These regulatory options are discussed in detail in Chapter 5 of this document. The control techniques on which these options are based are discussed in Chapter 4.

To control excess benzene process emissions from EB/S plants, the Administrator considered four alternatives: (1) Regulatory Option 1 -- Require that excess emissions during startup, shutdown, and malfunctions be combusted by one or more smokeless flares at all times during startup, shutdown, and malfunctions; (2) Regulatory Option 2 -- Require that EB/S owners or operators install backup compressors to control emissions during malfunctions and to combust the emissions by one or more smokeless flares during startup and shutdown and until the backup compressor is on line; (3) Regulatory Option 3 -- Require that EB/S owners or operators retrofit existing boilers to accept all excess emissions at all times; and (4) Regulatory Option 4 -- Require 100 percent excess benzene emissions reduction based on EB/S plant closures and substitutes for styrene. Because there are no technological reasons to consider different or alternative controls for new or existing sources, these regulatory options apply to all EB/S plants. These alternatives are discussed in detail in an addendum to this document.

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*The term "boiler" includes process heaters and superheaters.

1.2 ENVIRONMENTAL IMPACTS

The beneficial and adverse economic, environmental, and energy impacts associated with each regulatory option for both continuous and excess process emissions are summarized in Table 1-1 for continuous vent streams and Table 1-2 for excess emissions from EB/S plants. The environmental impacts are considered in terms of air quality, water quality, solid waste generation, flare noise, and flare thermal radiation. These are discussed in detail in Chapter 6 of this document.

In terms of nationwide air quality impacts, estimated total benzene emissions from continuous process vent streams alone within the EB/S industry are 1,990 megagrams per year (Mg/yr) at current control levels and production at 100 percent capacity. Regulatory Options A, B, and C would reduce total benzene continuous process emissions from the industry to 625 Mg/yr, 200 Mg/yr, and 70 Mg/yr, respectively. The estimated total nationwide excess benzene emissions from process vents within the EB/S

TABLE 1-1. MATRIX OF ENVIRONMENTAL AND ECONOMIC IMPACTS OF REGULATORY ALTERNATIVES FOR PROCESS VENT STREAMS

Administrative Action	Air Impact	Water Impact	Solid Waste Impact	Energy Impact	Noise Impact	Thermal Radiation	Economic Impact
Regulatory Option A	$+2^{**}$	-1^{**}	0	-1^{**}	0	0	-1^{**}
Regulatory Option B	$+3^{**}$	-1^{**}	0	-1^{**}	-1^{**}	-1^{*}	-1^{**}
Regulatory Option C	$+4^{**}$	0	0	$+1^{**}$	0	0	$+1^{**}$
Regulatory Option D	$+4^{**}$	0	0	0	0	0	-4^{***}
Delayed Standards	-2^{***}	0	0	0	0	0	0
No Standards	-3^{***}	0	0	0	0	0	0

KEY

+	Beneficial Impact
-	Adverse Impact
0	No Impact
1	Negligible Impact
2	Small Impact
3	Moderate Impact
4	Large Impact
*	Short-Term Impact
**	Long-Term Impact
***	Irreversible Impact

TABLE 1-2. MATRIX OF ENVIRONMENTAL AND COST IMPACTS OF REGULATORY ALTERNATIVES AND EXCESS EMISSIONS

Administrative Action	Air Impact	Water Impact	Solid Waste Impact	Energy Impact	Noise Impact	Thermal Radiation	Cost Impact
Regulatory Option 1	+4**	0	0	-1**	-1*	-1*	-1**
Regulatory Option 2	+4**	-1**	0	-1**	-1*	-1*	-3**
Regulatory Option 3	+4**	0	0	-1**	0	0	-4**
Regulatory Option 4	+4**	0	0	0	0	0	-4***
Delayed Standards	-4***	0	0	0	0	0	0
No Standards	-4***	0	0	0	0	0	0

KEY

+	Beneficial Impact
-	Adverse Impact
0	No Impact
1	Negligible Impact
2	Small Impact
3	Moderate Impact
4	Large Impact
*	Short-Term Impact
**	Long-Term Impact
***	Irreversible Impact

industry are 133 Mg/yr under current controls, 21 Mg/yr under Regulatory Option 1, 10 Mg/yr under Regulatory Option 2, and 1 Mg/yr under Regulatory Option 3.

The highest estimated maximum annual average benzene concentrations which occur from continuous process vents within the industry including emissions from fugitive and storage sources occur at 160 meters (m) for each option and are 95.6 parts per billion (ppb) under existing conditions, 54.1 ppb under Regulatory Option A, 46.1 ppb under Regulatory Option B, and 46.0 ppb under Regulatory Option C. The highest estimated maximum annual average emissions within the industry from the process vents alone are estimated at 63.6 ppb under existing conditions, 18.2 ppb under Regulatory Option A at a distance of 160 m, 1.4 ppb under Regulatory Option B at a distance of 500 m, and 0.19 ppb for Regulatory Option C at a distance of 1,000 m.

For excess benzene emissions, the estimated highest maximum annual average benzene concentrations under uncontrolled conditions occur at 160 m and are 7.9 ppb. The estimated highest maximum annual average benzene concentrations occur at 2,000 m for each regulatory option and are 4.3×10^{-3} ppb under Regulatory Option 1, 1.4×10^{-3} ppb under Regulatory Option 2, and 2.0×10^{-4} ppb under Regulatory Option 3.

None of the regulatory options considered result in any significant increase in wastewater or effluent discharge by EB/S plants nor do they generate any solid waste. Noise and thermal radiation associated with the use of flares, which would be required for reducing benzene emissions from continuous process stream sources if Regulatory Option B were adopted and under Regulatory Options 1, 2, and 3 for excess emissions, are negligible.

Under Regulatory Option A, energy is required to operate pumps and compressors for the condensers and absorbers. Energy also is required for the cooling system of the condensers. Total energy required for this control system is less than 0.1 percent of the fuel requirement for the model plant. Under Regulatory Option B, flare operation consumes both steam (for smoke control) and natural gas (as a supplemental fuel). In conjunction with the condensers and absorbers, the total energy demand for Regulatory Option B also would be less than 0.1 percent of the fuel requirements for the model plant. Due to recovered energy, Regulatory Option C provides a small net energy savings, equivalent to less than 0.1 percent of the fuel requirements for the model plant.

In terms of nationwide impacts, Regulatory Options A and B for all existing EB/S plants would result in a total energy demand of less than 0.1 percent of the nationwide EB/S energy demand. Due to recovered energy, Regulatory Option C would result in a small energy savings, equivalent to less than 0.1 percent of the current nationwide EB/S fuel requirements.

For excess emissions, energy is used in the production of steam to ensure smokeless operation of a ten-inch flare for combusting vent streams during startup, shutdown, and malfunction and for natural gas for pilot and purge operations. These energy requirements are negligible. Under Regulatory Option 1, steam and natural gas requirements are approximately 5.23×10^6 megajoules per year (MJ/yr) based on an average of 12 hours of operation per year for a 300,000 Mg/yr model plant. Under Regulatory Option 2, energy requirements for steam and natural gas are approximately 5.14×10^6 MJ/yr. Under Regulatory Option 3, energy requirements for steam and natural gas are approximately 5.1×10^6 MJ/yr.

In terms of nationwide energy impacts, assuming no current emissions control, Regulatory Option 1 would require 71 x 10^6 MJ/yr, Regulatory Option 2 would require 70 x 10^6 MJ/yr, and Regulatory Option 3 would require 69 x 10^6 MJ/yr of energy, or approximately 11,200 billions of barrels per year (bbl/yr) (fuel oil equivalent) for all existing plants under each option.

1.3 ECONOMIC IMPACTS

The Administrator considered both capital and annualized costs for controlling process vent streams under Regulatory Options A, B, and C. These are discussed in detail in Chapter 7. Nationwide impacts were determined from these cost estimates.

Regulatory Option A (85 percent control) would result in capital costs per plant ranging from zero to $268,000, total annualized costs ranging from $13,500 to a savings of $172,000, a potential maximum styrene price increase of $0.70/Mg (0.15 percent of product price), and no projected plant closures. A standard based on Regulatory Option B (94 percent control) would result in capital costs per plant ranging from zero to $530,000, total annualized costs ranging from $45,000 to a savings of $172,000, a potential maximum styrene price increase of $2.14/Mg (0.46 percent of product price), and no projected plant closures. Regulatory Option C (99 percent control) would result in capital costs per plant ranging from zero to $555,000, total annualized costs ranging from $26,000 to a savings of $150,000, a potential maximum styrene price increase of $1.27/Mg (0.27 percent of product price), and no projected plant closures. Regulatory Option D (100 percent control) would have the most severe economic impact on the EB/S industry, requiring closure of all EB/S production facilities. Plants producing styrene derivatives also may close depending upon the availability of foreign suppliers or substitutes.

In terms of nationwide impacts, Regulatory Options A, B, and C each would require 12 plants to install controls. Total nationwide capital costs to the industry would be approximately $1.4 million, $3.1 million, and $3.4 million under Regulatory Options A, B, and C, respectively. The industry's total annualized cost, assuming full utilization of capacity and including operating and maintenance costs, annualized capital costs, and fuel and recovered material credits, would be net credits of approximately $608,000 under Regulatory Option A, approximately $202,000 under Regulatory Option B, and approximately $460,000 under Regulatory Option C.

Capital costs also were estimated for controlling excess emissions under Regulatory Options 1, 2, 3, and 4. Regulatory Option 1 would require the smallest capital outlay of the regulatory options. Industry-wide capital costs of Regulatory Option 1 would be approximately $524,000 and would require four plants to install controls. Regulatory Option 2 would require capital outlays of approximately $5.5 million and would require six plants to install controls. Regulatory Option 3 would require the greatest capital outlays of approximately $20.0 million and would require 13 plants to install controls. Industry-wide annualized costs for Regulatory Options 1, 2, and 3 would be $171,000, $1.6 million, and $5.2 million, respectively.

As with Regulatory Option D for process vent streams, Regulatory Option 4 (100 percent control) would have the most severe economic impact on the EB/S industry, requiring closure of all ethylbenzene and styrene production facilities. Plants producing derivatives also may close depending upon the availability of foreign suppliers or substitutes.

2. INTRODUCTION

2.1 BACKGROUND

The Environmental Protection Agency proposed on October 10, 1979, "Policies and Procedures for Identifying, Assessing, and Regulating Airborne Substances Posing a Risk of Cancer" (44 FR 58642). All standards for carcinogens regulated under section 112 of the Clean Air Act are being developed in accordance with those proposed Policies and Procedures. The following is a section quoted from the Policies and Procedures which describes the procedures for establishing standards once the decision has been made as to which pollutants are to be regulated.

(2) The Proposed EPA Approach

The standard-setting policy proposed today requires, as a minimum, the use of "Best Available Technology" (BAT) to control emissions from source categories presenting significant risks to public health. The policy would also require additional controls, as necessary, to eliminate "unreasonable residual risks" remaining after the use of BAT. This approach is a judgmental one, designed to protect the public health with an ample margin of safety from risks associated with exposure to airborne carcinogens. The implementing procedure described below puts prime emphasis on public health, consistent with section 112, but permits consideration of economic impacts and benefits of the activity in setting standards for each source category. Uncertainties in the assessments of risks, costs, and potential benefits, as well as the distributional (equity) problems of various situations, also would be considered in setting standards.

(a) Source Categories Regulated

The first step in establishing standards and requirements for pollutants listed under section 112 under this proposed policy is the determination of which categories of sources emitting the pollutants will be regulated, and in what order regulations will be developed. Although a pollutant may have been listed because emissions from a particular source category pose a significant risk, other source categories also may emit the pollutant in lesser amounts. This may occur, for example, because the sources process very little of the substance, because the substance is present in only trace amounts in the sources' raw materials, or because sources have installed adequate controls on their own initiative or in response to other regulatory requirements.

The Administrator therefore will propose regulations only for those source categories which may pose significant risks to public health. The determination of whether a source category emitting a listed pollutant poses a significant risk will be made on essentially the same basis as the listing decision, except that the more detailed exposure analysis and risk assessment then available will be used in lieu of the preliminary information used in the listing decision. As in the listing decision, the risk assessment will be used to indicate the existence of a significant risk where the exposure analysis alone is insufficient, but will not be used as evidence that a significant risk does not exist where the exposure analysis indicates to the contrary.

(b) Priorities for the Development of Standards

EPA anticipates that a substantial number of substances will be listed as carcinogenic air pollutants under section 112 in the near future. It is also likely that many of these substances will be emitted in significant quantities from more than one source category. As a result, EPA will need to develop emission standards and other requirements for a large number of source categories emitting these substances. At least until generic standards can be developed for large groups of these sources, the resources that would be necessary to complete this task immediately far exceed those available to EPA for this purpose. Today's proposal therefore provides for the assignment of priorities to significant source categories for the development of these regulations, through publicly stated criteria and announced decisions.

Under today's proposal, source categories posing significant risks will be assigned priority status (high, medium, or low) for further regulatory action (beyond generic standards) on the basis of: (1) magnitude of projected total excess cancer incidence associated with current and future source emissions; (2) magnitude of cancer risks for the most exposed individuals; (3) ease of expeditious standards development and implementation; and (4) feasibility of significant improvements in controls. In addition, significant sources of more than one carcinogen may be given priority over single-pollutant sources, based on the sum of risks from the emitted substances.

A high priority will be assigned, for example, to a source category constituting an important problem requiring immediate attention, or where risks are somewhat lower but an appropriate regulatory solution is both feasible and readily available. Source categories assigned medium priority will generally be those that present lower risks and will be scheduled for standard development as resources become available. Lower risk source categories for which the extent of feasible control may be limited substantially will be assigned low priority for regulation development. Assignment to the low priority category will generally mean that active development of the regulations will not begin until there is some change in the factors which led to the assignment, or until higher priority actions have been completed.

(c) Regulatory Options Analysis

EPA will perform detailed analyses to identify alternative, technologically feasible control options and the economic, energy, and environmental impacts that would result from their application. Where substitution is determined to be a feasible option, the benefits of continued use of the substance or process will be considered. These analyses will rely primarily on the procedures and techniques employed by EPA for developing New Source Performance Standards under section 111 of the Act.

The identification of feasible control options initially will survey the existing control devices at the sources within a particular category to determine the best controls currently in use. The potential emission points of the listed pollutant at a particular kind of facility also will be identified, as will possible emissions of carcinogens other than the specific one under study. EPA will, in addition, examine the applicability of available technologies which are not currently used by the industry to control the pollutant of concern (technology transfer) but which have been demonstrated in pilot tests or other industrial applications. Finally, the availability and adequacy of substitutes which would eliminate some or all emissions of the pollutant will be assessed.

Once the technologically feasible control alternatives, which may range from no further control to a complete ban on emissions, have been identified, the environmental, economic, and energy impacts of these options will be determined. Considerations in these impact assessments will include for each option: the number of plant closures predicted and the direct impact on employment and end product prices; the impact on growth and expansion of the industry; the resulting changes in profitability; capital availability for control equipment; the impacts from the availability of substitute products and foreign imports; the potential increases in national energy consumption; and the impacts on other environmental media including increased water pollution and solid waste disposal. On the basis of these assessments, one of the control options identified will be designated as the BAT for the control of emissions from the sources in the category. This level of control will be that technology which, in the judgment of the Administrator, is the most advanced level of control adequately demonstrated, considering economic, energy, and environmental impacts.

The control level designated "best available technology" may be different for new and existing facilities in a category. For practical purposes, this level of control for new sources will, as a minimum, be equivalent to that which would be selected as the basis for a New Source Performance Standard (NSPS) under section 111. The requirement of "best available control technology" for new sources would consider "economic feasibility" and would not preclude new construction.

The selection of BAT for existing sources may require consideration of the technological problems associated with retrofit and related differences in the economic, energy, and environmental impacts. In practice, BAT for existing sources would consider economic feasibility and would not exceed the most advanced level of technology that at least most members of an industry could afford without plant closures.

(d) Minimum Requirements for Existing Sources

Final section 112 standards will require existing sources in any regulated source category, as a minimum, to limit their emissions to the levels corresponding to the use of "best available technology." This requirement is based on the Administrator's judgment that any risks that could be avoided through the use of these feasible control measures are unreasonable. Whether BAT controls are sufficient to protect public health will be determined by a subsequent evaluation of the remaining risks.

(e) Determination of Unreasonable Residual Risk for Existing Sources

Following the identification of BAT for existing sources, the quantitative risk assessment described earlier will be used to determine the risks remaining after the application of BAT to the source category. If the residual risks are not judged by the Administrator to be unreasonable, further controls would not be required. If, however, there is a finding of unreasonable residual risk, a more stringent alternative would be required. Among the possible alternatives would be the immediate application of more restrictive emission standards, including those based on more extensive use of substitutes, and scheduled or phased reductions in permissible emissions. The alternative selected would be that necessary, in the Administrator's judgment, to eliminate the unreasonable residual risks.

Given the differences in the degree of certainty in risk estimates, in the numbers of people exposed, in benefits, in the distribution of risks and benefits, in the cost of controls, in the availability of substitutes, and in other relevant factors, it is not possible to state any precise formula for determining unreasonable residual risk. The determination will necessarily be a matter of judgment for each category involved. Nevertheless, the process followed and the various factors involved can be outlined.

The determination of unreasonable residual risk will be based primarily on public health, and will require protection with an ample margin of safety. To the extent possible, quantitative or qualitative estimates of various factors will be made for purposes of comparison. Among these are: (1) the range of total expected cancer incidence and other health effects in the existing and future exposed populations through the anticipated operating life of existing sources; (2) the range of health risks to the most exposed individuals; (3) readily identifiable benefits of the substance or activity; (4) the economic impacts of requiring additional control measures; (5) the distribution of the benefits of the activity versus the risks it causes; and (6) other possible health and environmental effects resulting from the increased use of substitutes.

3. THE ETHYLBENZENE/STYRENE INDUSTRY

3.1 GENERAL

This chapter describes the ethylbenzene/styrene (EB/S) industry structure, its production process, and the associated emissions. A more detailed discussion of the EB/S industry structure is provided in Section 7.1. The processes described in this chapter are production of ethylbenzene from (1) benzene alkylation and (2) mixed xylene extraction and production of styrene from (1) ethylbenzene dehydrogenation and (2) ethylbenzene hydroperoxidation.

3.2 ETHYLBENZENE/STYRENE INDUSTRY

For this analysis, production of ethylbenzene and styrene is considered a single industry since 99 percent of ethylbenzene is used to produce styrene and styrene is produced only from ethylbenzene. In fact, in many EB/S facilities, ethylbenzene is not separated as a product itself but used only as an intermediate for styrene production. Furthermore, more than 90 percent of ethylbenzene is not sold on the market but is used by the producing company. Thus, growth of ethylbenzene and styrene production are intimately connected.[1,2]

3.2.1 Uses and Growth

Polymer manufacture consumes virtually all produced styrene. The production of polystyrene, used primarily in packaging and disposable serviceware, accounts for more than one-half of the styrene produced. Other major styrene polymers are acrylonitrile-butadiene-styrene (ABS) plastics and styrene-butadiene rubbers (SBR). The principal uses for ABS are pipe and automotive parts; the principal use for SBR is pneumatic tires. Table 3-1 shows styrene uses, percentages of consumption, and expected growth rates.[3,4]

TABLE 3-1. STYRENE CONSUMPTION AND GROWTH[5]

	1976 Consumption		Expected 1976 to 1980
	%	10^3 Mg/yr	Growth Rate, Percent
Polystyrene	54	1,547	7.0
Styrene copolymer resins*	17	467	7.0
Styrene-butadiene rubbers	9	258	2.5
Unsaturated polyester resins	6	171	9.0
Miscellaneous	1	28	12.5
Exports	13	372	-25.0
	100	2,843	

---

*Includes acrylonitrile-butadiene-styrene resins (ABS), eight percent of styrene consumption; styrene-butadiene resins, six percent; and other styrene copolymer resins, three percent.

3.2.2 Domestic Producers

The current U.S. styrene capacity is 4,092,000 Mg/yr (4,509,000 tons). In 1978, production was approximately 78 percent of total capacity. For ethylbenzene, the current U.S. capacity is 4,742,000 Mg/yr (5,226,000 tons). In 1978, production was approximately 70 percent of total capacity. By the end of 1982, based on a projected six percent annual growth in both styrene production and ethylbenzene consumption, styrene production levels should nearly equal capacity and ethylbenzene production should be 90 percent of capacity.

Currently, 14 companies produce ethylbenzene at 15 sites in the U.S. At ten of these sites, both styrene and ethylbenzene are produced in an integrated process. At the five remaining sites, only ethylbenzene is produced. Eleven companies produce styrene at 12 sites in the U.S. At ten sites both ethylbenzene and styrene are produced, while at two sites styrene alone is produced. Table 3-2 lists these ethylbenzene or styrene producers, their locations, capacities, and processes. Figures 3-1 and 3-2 indicate the site locations.

TABLE 3-2. U.S. ETHYLBENZENE/STYRENE CAPACITIES[a]

Company	Ethylbenzene Capacity (10^3 Mg/yr)	Ethylbenzene Process	Styrene Capacity (10^3 Mg/yr)	Styrene Process
American Hoechst Corp. Baton Rouge, LA[b]	526	c	450	e
Amoco, Texas City, TX	447	c	380	e
Atlantic Richfield Co., Port Arthur, TX	227	c		
Atlantic Richfield Co., Kobuta, PA			200	e
Charter, Houston, TX	18	d		
Commonwealth Oil Refining Co., Inc., Penuelas, PR	73	d		
Cos-Mar, Carville, LA	689	c	590	e
Dow Chemical U.S.A., Freeport, TX	847	c	680	e
Dow Chemical U.S.A., Midland, MI			181	e
El Paso Products Co., Odessa, TX	125	c	115	e
Gulf Oil Corp., Donaldsville, LA	313	c	272	e
Monsanto Company, Alvin, TX	23	d		
Monsanto Company, Texas City, TX	771	c,d	680	e
Oxirane, Channelview, TX	545	c	454	f
Sun Oil Co., Corpus Christi, TX	61	c,d	36	e
Tenneco, Chalmette, LA	16	d		
U.S. Steel, Houston, TX	61	d	54	e
TOTAL	4,742		4,092	

[a] See References 12 and 13.

[b] American Hoechst Corp. plans to bring a 408.2 x 10^3 Mg/yr styrene plant on-stream at Bayport, TX in 1980.

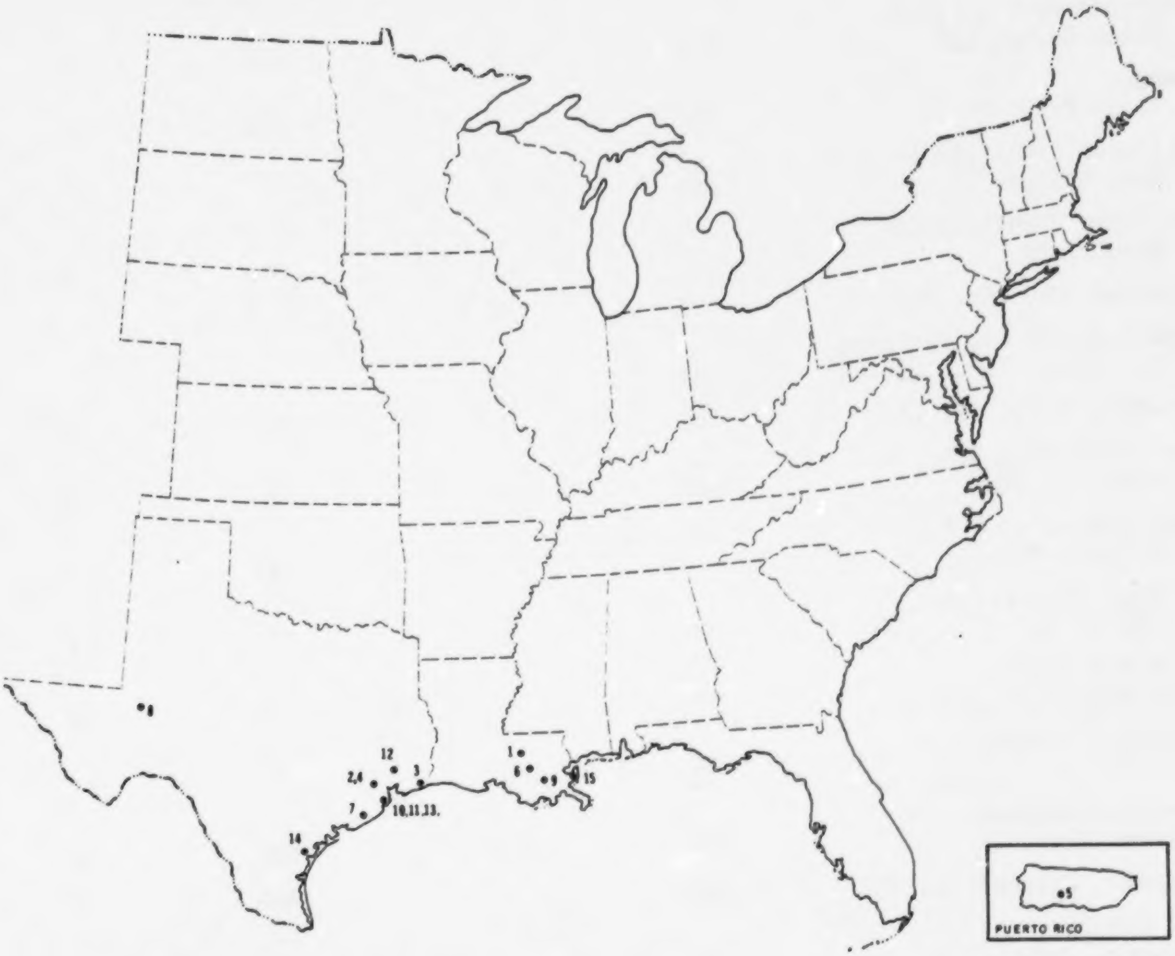
[c] Benzene alkylation.

[d] Mixed xylene stream recovery.

[e] Ethylbenzene dehydrogenation.

[f] Ethylbenzene hydroperoxidation.

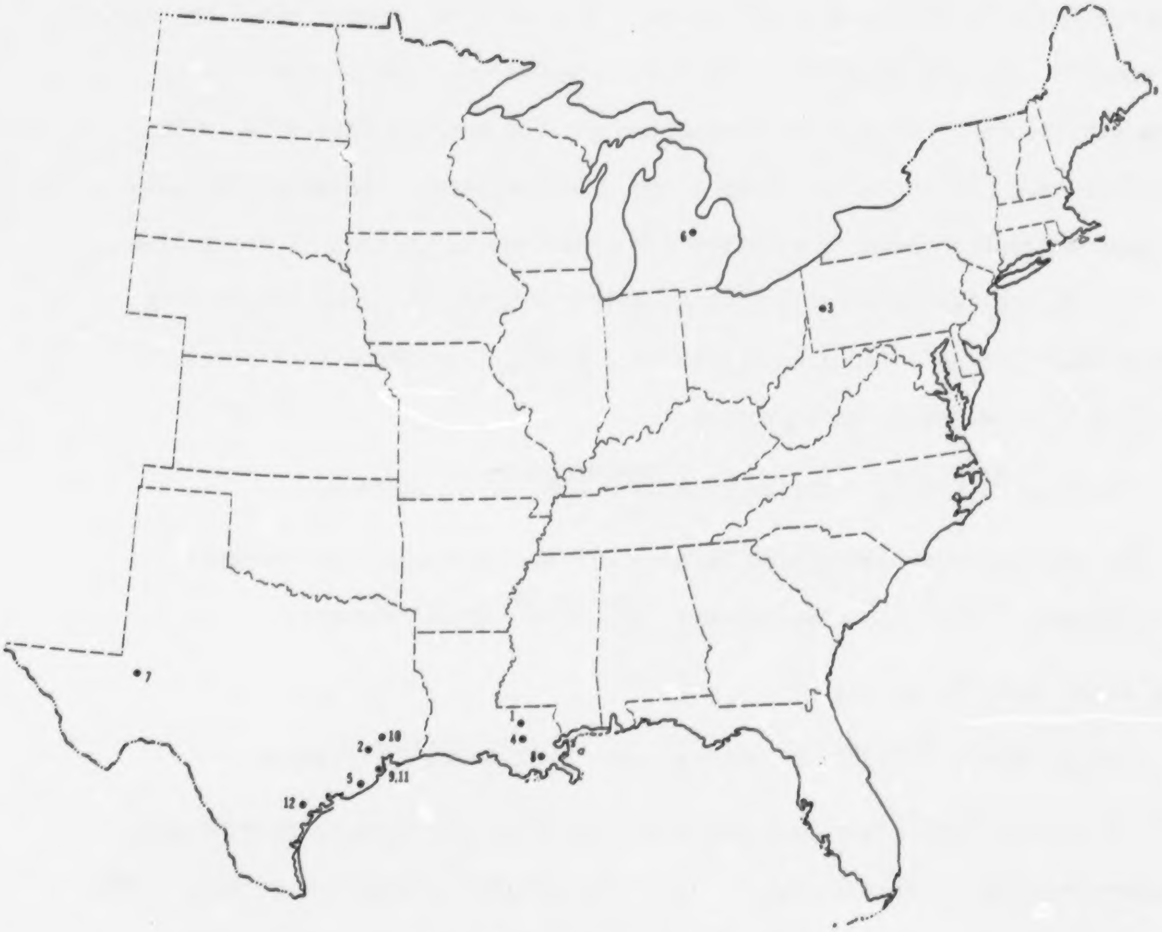
FIGURE 3–1
LOCATIONS OF PLANTS MANUFACTURING ETHYLBENZENE



LEGEND OF PLANT NAMES AND LOCATIONS

1. American Hoechst, Baton Rouge, LA
2. U.S. Steel, Houston, TX
3. Atlantic Richfield, Port Arthur, TX
4. Charter, Houston, TX
5. Commonwealth Oil, Penuelas, PR
6. Cos–Mar, Carville, LA
7. Dow, Freeport, TX
8. El Paso Products, Odessa, TX
9. Gulf, Donaldsonville, LA
10. Monsanto, Alvin, TX
11. Monsanto, Texas City, TX
12. Oxirane, Channelview, TX
13. Amoco, Texas City, TX
14. Sun Oil, Corpus Christi, TX
15. Tenneco, Chalmette, LA

FIGURE 3–2
LOCATIONS OF PLANTS MANUFACTURING STYRENE



LEGEND OF PLANT NAMES AND LOCATIONS

1. American Hoechst, Baton Rouge, LA
2. U.S. Steel, Houston, TX
3. Atlantic Richfield, Kobuta, PA
4. Cos–Mar, Carville, LA
5. Dow, Freeport, TX
6. Dow, Midland, MI
7. El Paso Products, Odessa, TX
8. Gulf, Donaldsonville, LA
9. Monsanto, Texas City, TX
10. Oxirane, Channelview, TX
11. Amoco, Texas City, TX
12. Sun Oil, Corpus Christi, TX

3.3 ETHYLBENZENE/STYRENE PRODUCTION PROCESSES[6,7,8,9]

The EB/S industry produces styrene from ethylbenzene by either (1) ethylbenzene dehydrogenation, or (2) ethylbenzene hydroperoxidation. The only U.S. application of the ethylbenzene hydroperoxidation process is the Oxirane Corporation unit in Channelview, Texas. This unit represents about ten percent of the U.S. styrene capacity. The two processes now used in the U.S. to make ethylbenzene for styrene production are (1) benzene alkylation with ethylene, and (2) extraction from mixed xylene streams. Benzene alkylation is the dominant process, accounting for more than 95 percent of production.

There are ten EB/S facilities at which both ethylbenzene and styrene are produced in an integrated operation. At eight of these facilities, styrene is produced by this process:

$$\text{Benzene} \xrightarrow{\text{Alkylation}} \text{Ethylbenzene} \xrightarrow{\text{Dehydrogenation}} \text{Styrene.}$$

Of the two remaining integrated EB/S facilities, one uses the process:

$$\text{Benzene} \xrightarrow{\text{Alkylation}} \text{Ethylbenzene} \xrightarrow{\text{Hydroperoxidation}} \text{Styrene;}$$

the other uses the process:

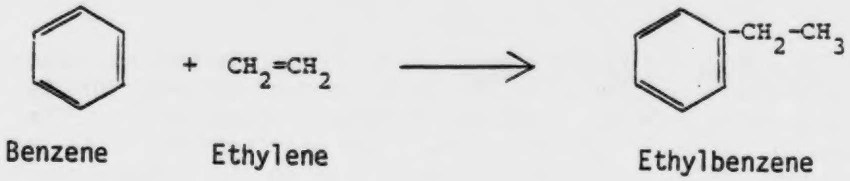
$$\text{Mixed Xylene} \xrightarrow{\text{Extraction}} \text{Ethylbenzene} \xrightarrow{\text{Dehydrogenation}} \text{Styrene.}$$

A typical EB/S plant uses benzene alkylation followed by ethylbenzene dehydrogenation to form styrene. This typical EB/S production process along with extraction of ethylbenzene from mixed xylenes and the ethylbenzene hydroperoxidation process is described below.

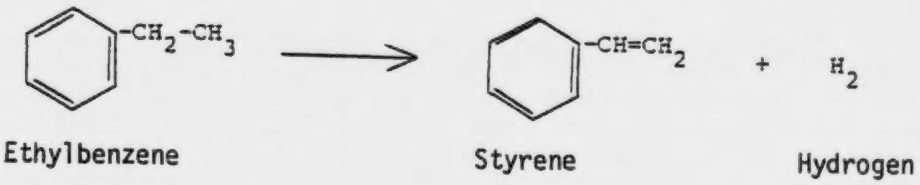
3.3.1 Benzene Alkylation and Ethylbenzene Dehydrogenation

The primary reactions shown below for the production of styrene are (1) catalytic alkylation of benzene with ethylene to produce ethylbenzene, and (2) catalytic dehydrogenation of ethylbenzene to produce styrene.

(1) Catalytic alkylation of benzene with ethylene to ethylbenzene:



(2) Catalytic dehydrogenation of ethylbenzene to styrene:



3.3.1.1 Basic Process

A step-by-step diagram of the benzene alkylation process and the ethylbenzene dehydrogenation process is shown in Figures 3-3 and 3-4. A detailed process flow diagram of the complete styrene process is shown in Figure 3-5.

(a) Step 1 -- Benzene Alkylation to Form Ethylbenzene. First, both feed and recycled benzene are dried to remove water. The dry benzene (99 percent) (Stream 1, Figure 3-5) and ethylene (95 to 99 percent) are fed continuously into the reactor operating at essentially atmospheric pressure. A small amount of ethyl chloride is added to the ethylene feed as a source of hydrogen chloride which acts as a catalyst promoter. The catalyst, granular aluminum chloride, is fed to the reactor at a constant rate.

The alkylation reaction occurs and is maintained at approximately 95°C by cooling water. The aluminum chloride combines with the benzene and ethylbenzene to form an insoluble complex. Next, the reactor effluent, which contains benzene, ethylbenzene, and the insoluble complex, goes to a settler, where the crude ethylbenzene is decanted and the heavy catalyst complex is recycled to the reactor. Approximately 80 percent of the aluminum chloride may be recovered. Reactor vent gas is routed through a condenser and scrubbers in the alkylation reaction section to recover any aromatics and to remove hydrogen chloride.

(b) Step 2 -- Treating Liquid Mixture from Alkylation Reactor. The crude ethylbenzene from the settler (Stream 2, Figure 3-5) is washed with water and neutralized with a caustic solution to remove traces of chlorides. Then the crude ethylbenzene is fed to the ethylbenzene purification section.

(c) Step 3 -- Purifying the Ethylbenzene. The crude ethylbenzene consists of 36 to 42 percent ethylbenzene, 40 to 55 percent benzene, and ten to 20 percent polyethylbenzene (PEB) and high-boiling materials. The first phase in the purification of the crude ethylbenzene is to separate and remove benzene (Stream 3, Figure 3-5) in the benzene recovery column. After distillation to remove water, the dry benzene is returned to the alkylation reactor. In the second phase, the product ethylbenzene (Stream 4, Figure 3-5) is separated from the remaining high-boiling materials and PEB in the ethylbenzene recovery column. Finally, the high-boiling materials are distilled in the PEB column to separate the residue oil from the PEB which is recycled.

(d) Step 4 -- Ethylbenzene Dehydrogenation to Produce Styrene. The purified ethylbenzene is preheated with steam (to 160°C) and by heat exchange (to 520°C). Superheated steam (710°C) and the ethylbenzene vapors are mixed continuously and fed into the reactor. The reactor contains a selective, fixed dehydrogenation catalyst such as zinc, aluminum, chromium, iron, or magnesium oxide. The dehydrogenation of ethylbenzene to form styrene occurs.

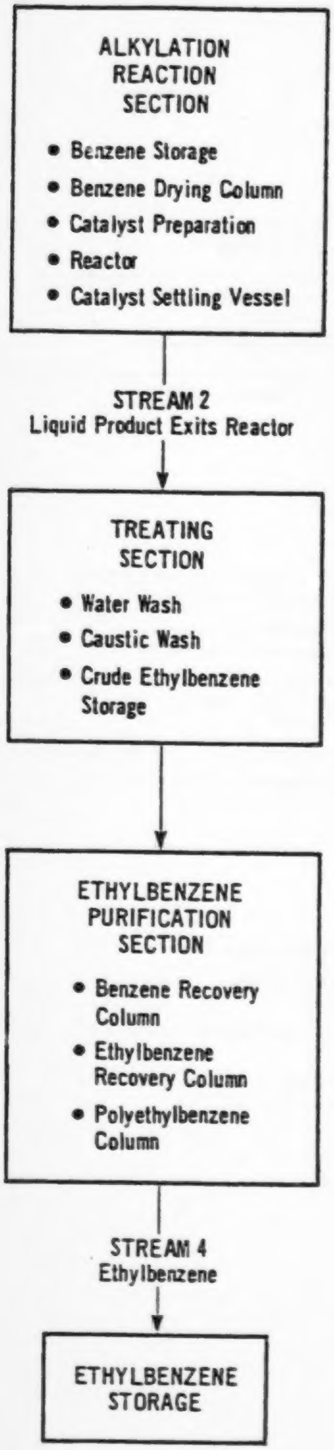
The reaction product leaves the top of the reactor and is cooled first by the incoming ethylbenzene and then by steam in heat exchangers. The mixture then goes through a water-cooled and/or air-cooled condenser, where the steam and crude styrene vapor are condensed, and then flows to the separators.

(e) Step 5 -- Separating Crude Styrene from Other Reaction Products. In this step, the liquid crude styrene, consisting of water, styrene, ethylbenzene, toluene, benzene, and high-boiling materials, and the vent gases, hydrogen, carbon monoxide, carbon dioxide, and hydrocarbons, are separated.

After separation, the condensable hydrogen-rich gas (Stream 9, Figure 3-5) is sent to the recovery section; the process water condensate is decanted (Stream 10, Figure 3-5) and goes to a stripper; and the remaining crude styrene (Stream 11, Figure 3-5) is sent to the styrene purification section. The hydrogen-rich gas (Stream 9, Figure 3-5) is compressed and then cooled in the recovery section to recover aromatic organics, which are returned to the process. After removal of the organics, the hydrogen-rich gas (Stream 12, Figure 3-5) usually is sent to the steam superheater, where it is used as fuel. The process water condensate (Stream 10, Figure 3-5) is fed to the process water stripper, where dissolved aromatic organics are removed and returned to the process. The purified water is sent to the plant boiler for use as a boiler feedwater.

(f) Step 6 -- Purifying the Styrene. In the styrene purification section, benzene and toluene (Stream 13, Figure 3-5) are first separated from the crude styrene in the benzene-toluene column. The benzene and toluene then typically are separated by distillation; the toluene is sold and the benzene is either sold or recycled. The recycled ethylbenzene (Stream 6, Figure 3-5) is separated from the styrene and tars in the ethylbenzene recycle column and reprocessed. Finally, the product styrene (Stream 14, Figure 3-5) is separated from the tars in the styrene finishing column.

FIGURE 3–3
BENZENE ALKYLATION PROCESS


ALKYLATION REACTION SECTION
• Benzene Storage
• Benzene Drying Column
• Catalyst Preparation
• Reactor
• Catalyst Settling Vessel
STREAM 2
Liquid Product Exits Reactor
TREATING SECTION
• Water Wash
• Caustic Wash
• Crude Ethylbenzene Storage
ETHYLBENZENE PURIFICATION SECTION
• Benzene Recovery Column
• Ethylbenzene Recovery Column
• Polyethylbenzene Column
STREAM 4
Ethylbenzene
ETHYLBENZENE STORAGE

STEP 1

BENZENE ALKYLATION TO FORM ETHYLBENZENE

a. Benzene is dried

b. Benzene, ethyl chloride, and aluminum chloride catalyst are fed to reactor

c. Alkylation reaction occurs

d. Catalyst is recovered

STEP 2

TREATING THE LIQUID MIXTURE FROM ALKYLATION REACTOR

a. Crude ethylbenzene is washed with water and caustics to remove chlorides

STEP 3

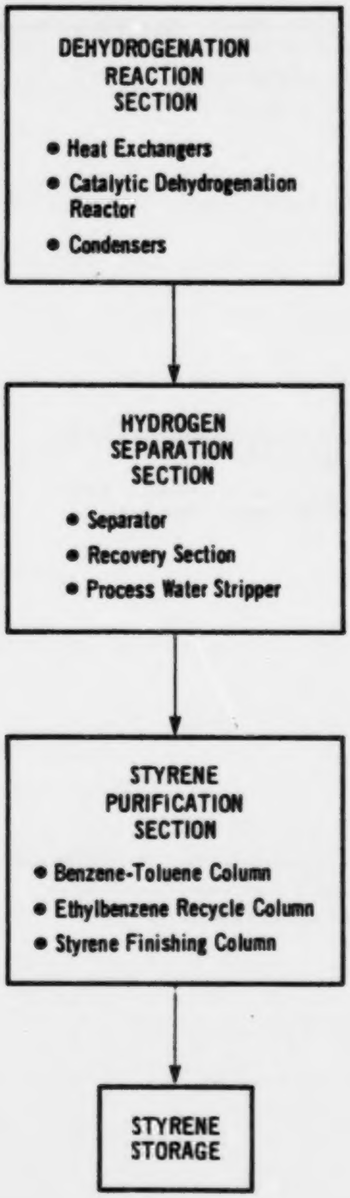
PURIFYING ETHYLBENZENE

a. Benzene is separated from crude ethylbenzene

b. Ethylbenzene is separated from 'heavies'

c. Polyethylbenzenes are recovered

FIGURE 3-4
ETHYLBENZENE DEHYDROGENATION PROCESS


DEHYDROGENATION REACTION SECTION
• Heat Exchangers
• Catalytic Dehydrogenation Reactor
• Condensers
HYDROGEN SEPARATION SECTION
• Separator
• Recovery Section
• Process Water Stripper
STYRENE PURIFICATION SECTION
• Benzene-Toluene Column
• Ethylbenzene Recycle Column
• Styrene Finishing Column
STYRENE STORAGE

STEP 4

DEHYDROGENATING ETHYLBENZENE TO PRODUCE STYRENE

a. Ethylbenzene is vaporized and superheated, mixed with superheated steam, and fed to reactor

b. Dehydrogenation reaction occurs

c. Reaction mixture is cooled and crude styrene and water are condensed

STEP 5

SEPARATING CRUDE STYRENE FROM OTHER REACTION PRODUCTS

a. Non-condensible hydrogen-rich gas is separated from water-styrene mixture

b. Hydrogen-rich gas is compressed and cooled to remove aromatic organics and then burned

c. Water is removed from styrene and purified

d. Styrene is sent to purification section

STEP 6

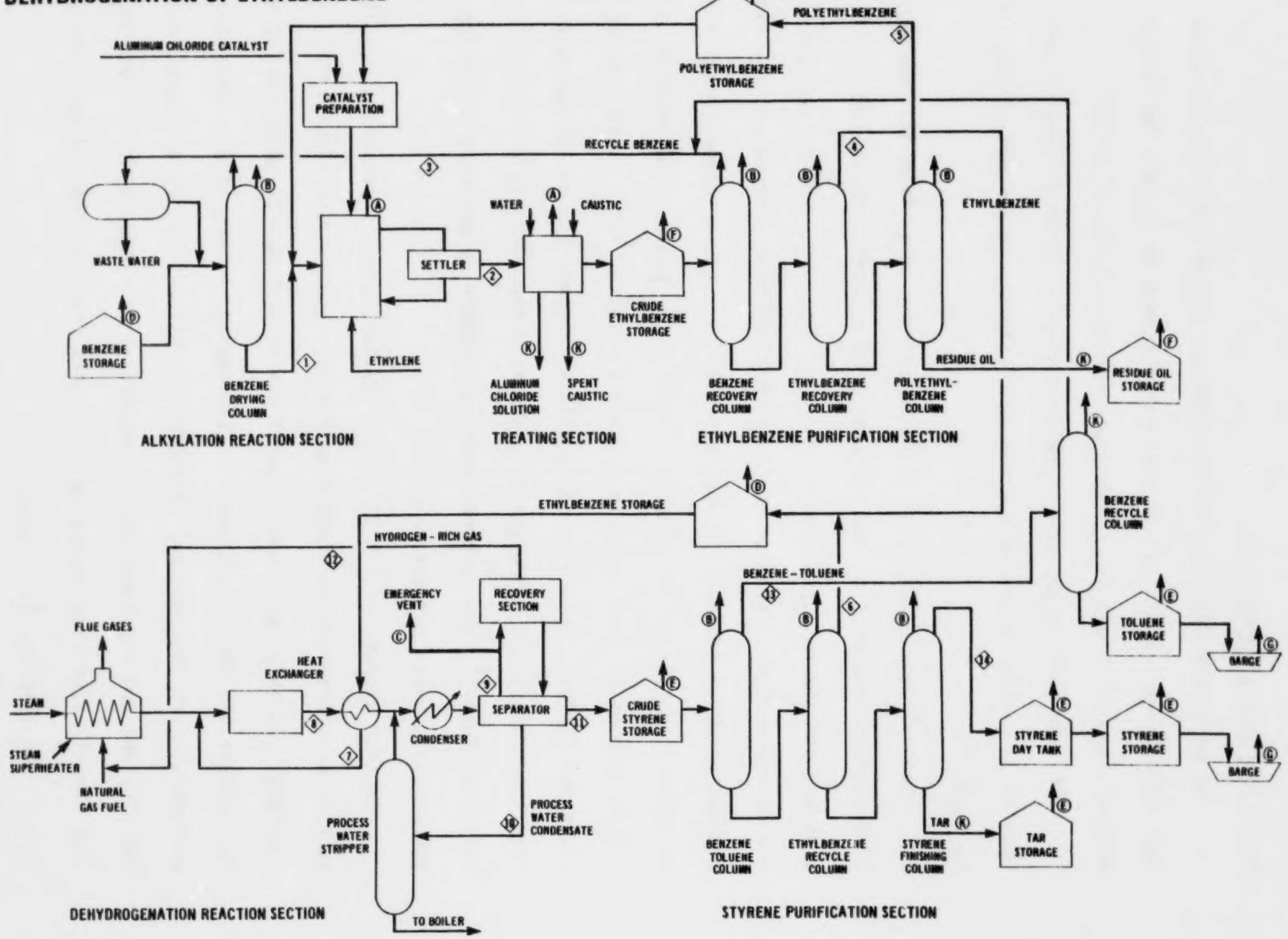
PURIFYING THE STYRENE

a. Benzene and toluene are separated from styrene

b. Unreacted ethylbenzene is separated from styrene

c. Styrene is separated from residue and sent to storage

FIGURE 3–5
PROCESS FLOW DIAGRAM, MODEL PLANT UNCONTROLLED, STYRENE FROM BENZENE AND ETHYLENE BY DEHYDROGENATION OF ETHYLBENZENE


ALUMINUM CHLORIDE CATALYST
CATALYST PREPARATION
POLYETHYLBENZENE
POLYETHYLBENZENE STORAGE
RECYCLE BENZENE
WASTE WATER
BENZENE STORAGE
BENZENE DRYING COLUMN
ETHYLENE
SETTLER
WATER
CAUSTIC
ALUMINUM CHLORIDE SOLUTION
SPENT CAUSTIC
CRUDE ETHYLBENZENE STORAGE
BENZENE RECOVERY COLUMN
ETHYLBENZENE RECOVERY COLUMN
POLYETHYL-BENZENE COLUMN
ETHYLBENZENE
RESIDUE OIL
RESIDUE OIL STORAGE
ALKYLATION REACTION SECTION
TREATING SECTION
ETHYLBENZENE PURIFICATION SECTION
ETHYLBENZENE STORAGE
HYDROGEN - RICH GAS
BENZENE RECYCLE COLUMN
BENZENE - TOLUENE
TOLUENE STORAGE
BARGE
FLUE GASES
EMERGENCY VENT
RECOVERY SECTION
HEAT EXCHANGER
STEAM
STEAM SUPERHEATER
NATURAL GAS FUEL
CONDENSER
SEPARATOR
CRUDE STYRENE STORAGE
STYRENE DAY TANK
STYRENE STORAGE
BARGE
PROCESS WATER STRIPPER
PROCESS WATER CONDENSATE
TO BOILER
TAR
TAR STORAGE
BENZENE TOLUENE COLUMN
ETHYLBENZENE RECYCLE COLUMN
STYRENE FINISHING COLUMN
DEHYDROGENATION REACTION SECTION
STYRENE PURIFICATION SECTION
A
B
C
D
E
F
G
K
1
2
3
4
5
6
7
8
9
10
11
12
13
14

3.3.1.2 Process Variations

The benzene alkylation and ethylbenzene dehydrogenation processes described above are typical of most ethylbenzene or styrene facilities. However, among the plants, several process variations do exist.

Ethylene used to produce styrene usually is 95 to 99 percent pure. However, a dilute stream containing as little as ten percent ethylene can be used.[10]

The pressure in the alkylation reactor can range from near ambient to 2759 kPa and temperatures may range from 80 to 400°C, depending on the pressure and the catalyst used. Some high-pressure, vapor-phase processes use solid catalysts, such as the newer Mobil/Badger process and the Alkar process by UOP. The Mobil/Badger process was used in a demonstration unit at American Hoechst's Baton Rouge, Louisiana,[11] plant. The Alkar process by UOP is used by El Paso Products Company at Odessa, Texas, with a boron trifluoride catalyst. El Paso uses a dilute ethylene stream (50 percent) to feed the process and sends the offgases from the alkylation reaction to its boiler as fuel.[12] This process does not produce by-products or sludge and the catalyst lasts for several years.[13]

Another process variation in the reaction step is operating the alkylator at pressures greater than atmospheric pressure with high-purity ethylene. In this variation, natural gas or nitrogen is added periodically to maintain the desired pressure in the reactor. Few, if any, emissions are vented from the reactor. Instead, the natural gas or nitrogen fed with the ethylene and any inert gases produced as by-products in the reactor go with the alkylate to a degassing step where they are removed when the pressure on the alkylate is reduced.

The dehydrogenation reactor can be operated either at constant temperature with heat added in the reactor or under adiabatic conditions with all the heat supplied by diluting the ethylbenzene feed entering the reactor with the superheated steam. After recovery of the aromatics, the hydrogen-rich offgas from the separator following the dehydrogenation reactor can be either burned as fuel or processed further to recover hydrogen or carbon dioxide for use in other processes.

A variation of the styrene purification process from that shown in Figure 3-5 is to first separate a mixture of ethylbenzene, toluene, and benzene from the styrene and tars. The ethylbenzene, toluene, and benzene stream then is fed to a column where the benzene and toluene are separated from the ethylbenzene. The high-boiling materials from the first separation go to another column, where the styrene is separated from the tars.

3.3.2 Ethylbenzene from Mixed Xylenes[14-17]

In addition to typical benzene alkylation to produce ethylbenzene, ethylbenzene also can be extracted from mixed streams. In fact, of the ten integrated EB/S operations, one plant extracts ethylbenzene from xylene streams and then dehydrogenates the ethylbenzene to produce styrene. Three plants producing only ethylbenzene also recover it from xylene streams. In contrast to benzene alkylation, which produces one major product and has definitive start and end points, mixed xylene extraction processes multicomponent streams in many steps for production of benzene, toluene, gasoline components, and other products. Since many of these steps do not involve pure ethylbenzene, the extraction process can be defined as the one step which distills ethylbenzene from xylene. However, upstream steps must be altered greatly to change the amount of ethylbenzene available from mixed xylene extraction. Thus, the extraction process will be reviewed starting with the sources of ethylbenzene-containing xylenes. Figure 3-6 shows a conceptual flow chart of the mixed xylene extraction process and Figure 3-7 shows the benzene, toluene, and xylene processing flow diagram.

3.3.2.1 Sources of Xylene Streams

The two major sources of such ethylbenzene-containing xylenes are (1) catalytic reformate from refineries, and (2) pyrolysis gasoline from the ethylene plant. The refinery reforming process produces aromatics by catalytically dehydrogenating a naphtha feed containing mainly alkanes in the 65°C (150°F) to 200°C (400°F) boiling range. The exact composition of the reformate depends on the catalyst, feed composition, and operating conditions. Table 3-3 shows a typical composition for reformate streams.

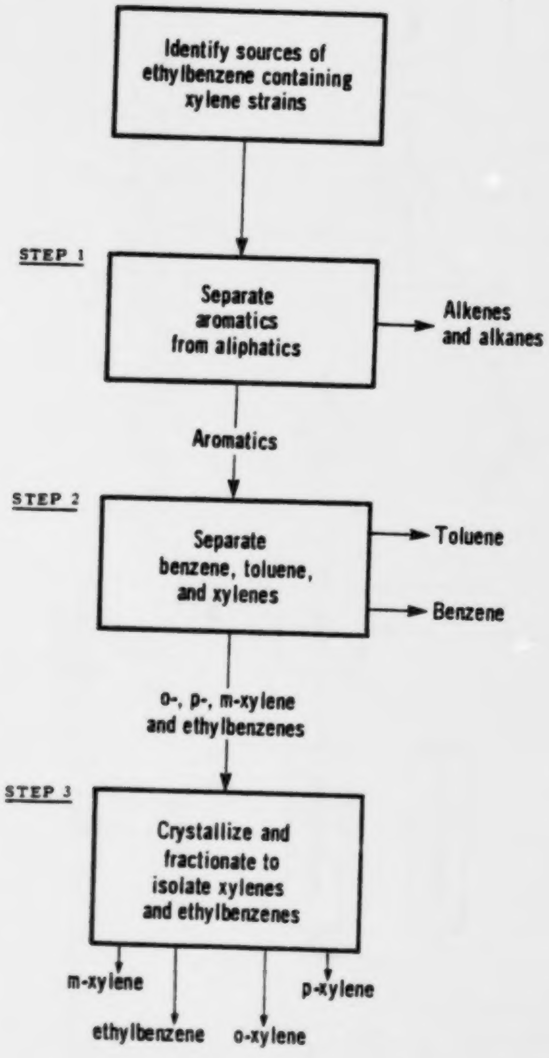
TABLE 3-3.[18] TYPICAL COMPOSITIONS OF XYLENE-CONTAINING STREAM

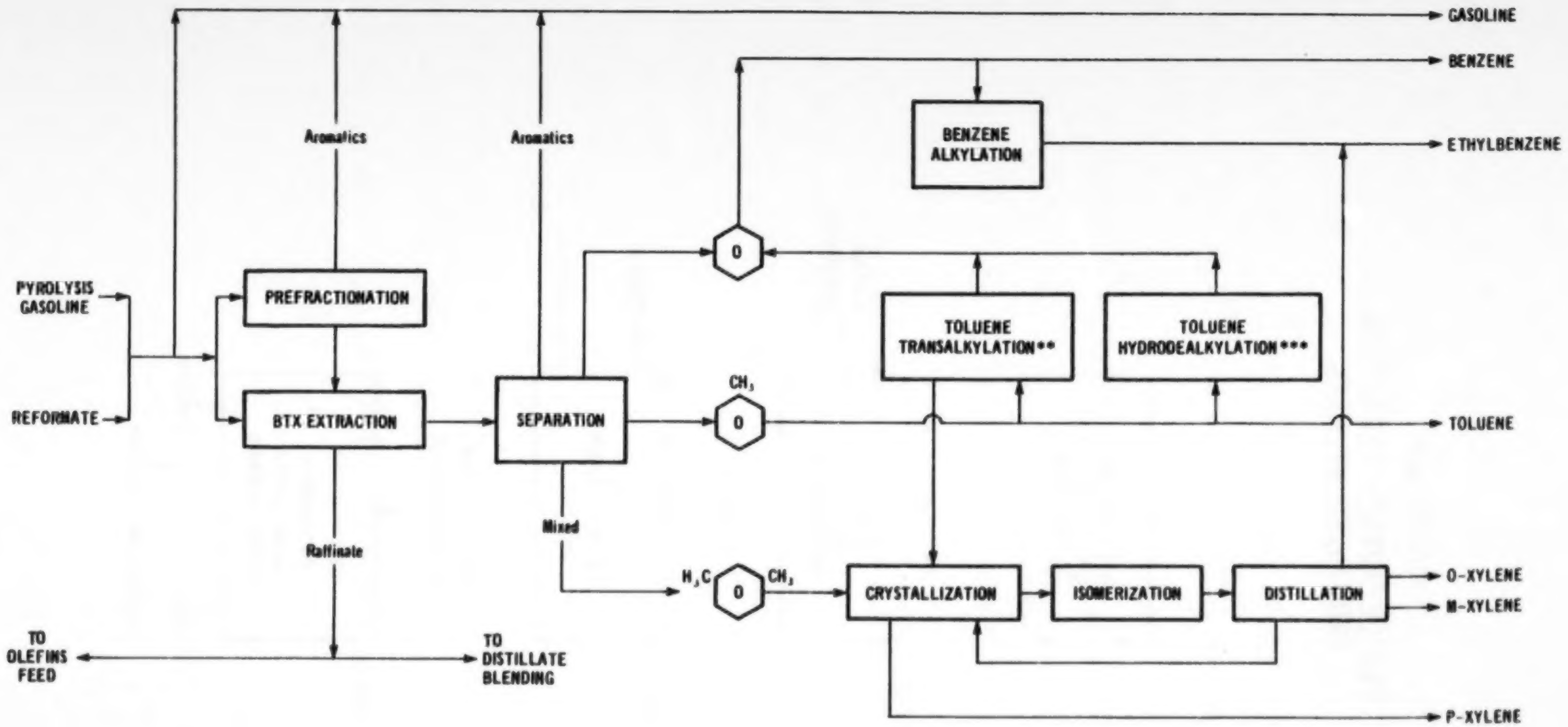
All Components	Refinery Reformate (volume percent)	Pyrolysis Gasoline (volume percent)
Benzene	5	32
Toluenes	24	14
Ethylbenzene	4	6
Xylenes o/m/p	5/9/4	1/3/1
C_9 + Aromatics	10	13
Non-Aromatics	39	30
C_8's Only		
Ethylbenzene	20	53
o-xylene	23	12
m-xylene	40	25
p-xylene	17	10

In the ethylene process, thermal cracking of various hydrocarbons produces short chain olefins. With newer ethylene plants moving to higher molecular weight hydrocarbon feeds, increasing amounts of ethylbenzene and xylene-containing streams (pyrolysis gasoline) will be available from ethylene

FIGURE 3–6

ETHYLBENZENE EXTRACTION FROM MIXED XYLENES


Identify sources of ethylbenzene containing xylene strains
STEP 1
Separate aromatics from aliphatics
Alkenes and alkanes
Aromatics
STEP 2
Separate benzene, toluene, and xylenes
Toluene
Benzene
o-, p-, m-xylene and ethylbenzenes
STEP 3
Crystallize and fractionate to isolate xylenes and ethylbenzenes
m-xylene
p-xylene
ethylbenzene
o-xylene


PYROLYSIS GASOLINE
REFORMATE
PREFRACTIONATION
BTX EXTRACTION
Aromatics
Aromatics
Raffinate
TO OLEFINS FEED
TO DISTILLATE BLENDING
SEPARATION
Mixed
O
CH₃
H₃C
BENZENE ALKYLATION
TOLUENE TRANSALKYLATION**
TOLUENE HYDRODEALKYLATION***
CRYSTALLIZATION
ISOMERIZATION
DISTILLATION
GASOLINE
BENZENE
ETHYLBENZENE
TOLUENE
O-XYLENE
M-XYLENE
P-XYLENE

* This diagram shows the important units associated with processing BTX streams to produce ethylbenzene. Note that both ethylbenzene from benzene alkylation and ethylbenzene from mixed xylene separation are shown. Also, for completeness, two units not discussed in the text are shown here: toluene transalkylation and toluene hydrodealkylation.

**Toluene Transalkylation–Toluene is converted to benzene and xylene by transfer of a methane group.

***Toluene Hydrodealkylation–Toluene is dealkylated in the presense of H_2 to produce methane and benzene.

FIGURE 3–7
BTX PROCESSING BLOCK FLOW DIAGRAM*

production. Table 3-3 shows typical aromatics yields in pyrolysis gasoline from ethylene plants.

3.3.2.2 Basic Process

The reformate and pyrolysis gasoline streams are either blended directly into gasoline or processed further for recovery of specific aromatics. This processing includes extracting aromatics, separating benzene-toluene-xylene (BTX), and processing mixed xylenes. Briefly, ethylbenzene is extracted from the xylene streams in the steps described below.

(a) Step 1 -- Aromatics Separation. Aromatics extraction removes the alkanes and alkenes from the reformate by preferential absorption of the aromatics in a suitable solvent. The aromatics are recovered from the solvent and sent to BTX separation; the alkanes and alkenes are sent to distillate oil blending or to olefins.

(b) Step 2 -- BTX Separation. In BTX separation, the aromatics first are pretreated to remove residual alkenes and then split by straight distillation to isolate the specific aromatics: benzene, toluene, and mixed xylenes. In cases in which only one or two aromatics are desired, the extraction step often is preceded by a prefractionation unit. This unit isolates a specific cut of the reformate boiling in a narrow range around the desired aromatic. The aromatic then is recovered by routing only this specific cut to extraction and sending the remaining aromatics to gasoline blending. Using such a prefractionation unit greatly reduces the size of the downstream extraction unit.

(c) Step 3 -- Crystallization and Fractionation. In producing xylenes, mixed xylenes from BTX separation typically are crystallized to produce p-xylene, fractionated to isolate o-xylene and small amounts of ethylbenzene and m-xylene, and isomerized to convert the remaining ethylbenzene and m-xylene to o- and p-xylene. Crystallization of mixed xylenes is required for separation since the close boiling points of m- and p-xylene make distillation impossible. Isomerization of mixed xylenes is used to enhance production of o- and p-xylene since demand for them is larger than their occurrence in mixed xylene streams. The fractionation of ethylbenzene and m-xylene requires very large distillation units. Since separation of m- and p-xylene by crystallization is costly, several new processes based on adsorption and extraction have been developed as alternatives.

At present, very little ethylbenzene is recovered in mixed xylene processing; production is less than 100,000 Mg/yr (110,000 tons) and capacity is less than 200,000 Mg/yr (220,000 tons). However, very large quantities are potentially available. Based on 1978 reformate and ethylene production capacities, more than 6 x 10^6 Mg/yr of ethylbenzene are available from these streams. Virtually all this ethylbenzene becomes a high octane component in gasoline or is converted to xylenes.

3.3.3 Styrene from Ethylbenzene Hydroperoxidation

In addition to the typical ethylbenzene dehydrogenation process, styrene is produced from ethylbenzene by a hydroperoxidation reaction.

3.3.3.1 Ethylbenzene Hydroperoxidation Capacity

The only U.S. application of the ethylbenzene hydroperoxidation process is the Oxirane Corporation unit in Channelview, Texas. This unit represents about ten percent of U.S. styrene capacity.

3.3.3.2 Basic Process

The basic process shown in Figures 3-8 and 3-9 is described below.

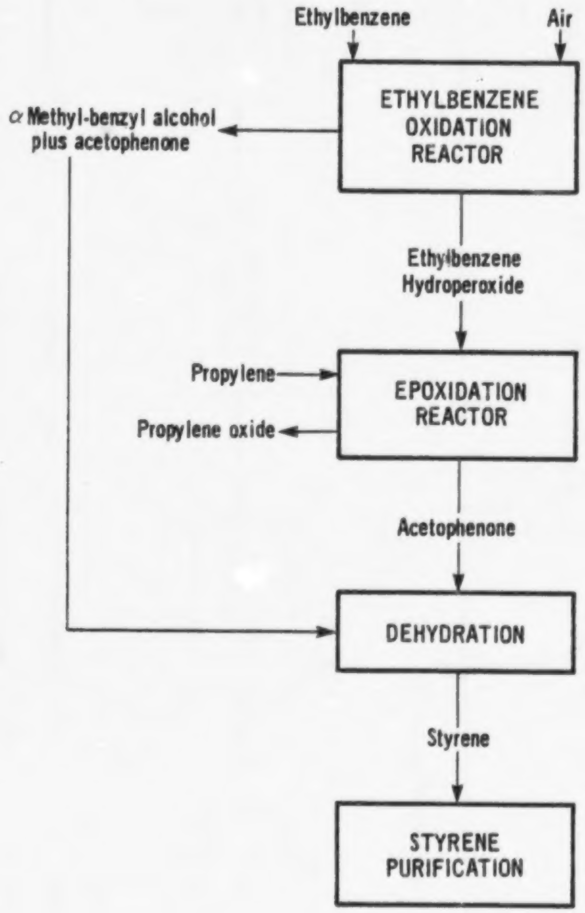
(a) Step 1 -- Ethylbenzene Oxidation. The initial step in the process is the oxidation of ethylbenzene with air to produce ethylbenzene hydroperoxide and minor amounts of a-methyl-benzyl alcohol and acetophenone. The exit gas from the reactor columns contains inert gas (principally nitrogen) and a mixture of organic vapors and is cooled and scrubbed to recover aromatics before venting.

After the oxidation reaction, the mixed organic stream is fed to an evaporation system where some of the unreacted ethylbenzene, along with low-boiling contaminates, is removed. The recovered ethylbenzene is sent to the ethylbenzene recovery system for treatment prior to reuse. The concentrated solution of ethylbenzene hydroperoxide and reaction by-products goes to the epoxidation reaction system.

(b) Step 2 -- Epoxidation of Propylene with Ethylbenzene Hydroperoxidation. Next, propylene is mixed with the concentrated ethylbenzene hydroperoxide solution and epoxidized over a proprietary catalyst mixture at high pressures to form propylene oxide. The main by-product of this reaction is acetophenone. After epoxidation, the pressure is reduced and most of the residual propylene and other low boilers are separated from the reaction mixture by a distillation system. The vent stream from this distillation system containing propane, propylene, and minor amounts of other gases is fed to the plant fuel gas manifold as fuel. The recovered propylene is recycled for reuse in the epoxidation reaction.

The crude epoxidate stream from the epoxidation reactor next is treated to remove the acidic impurities and residual catalyst by

FIGURE 3-8
ETHYLBENZENE HYDROPEROXIDATION PROCESS


Ethylbenzene
Air
ETHYLBENZENE OXIDATION REACTOR
α Methyl-benzyl alcohol plus acetophenone
Ethylbenzene Hydroperoxide
Propylene
Propylene oxide
EPOXIDATION REACTOR
Acetophenone
DEHYDRATION
Styrene
STYRENE PURIFICATION

STEP 1
Ethylbenzene oxidation to ethylbenzene hydroperoxide, α-methyl-benzyl alcohol, and acetophenone

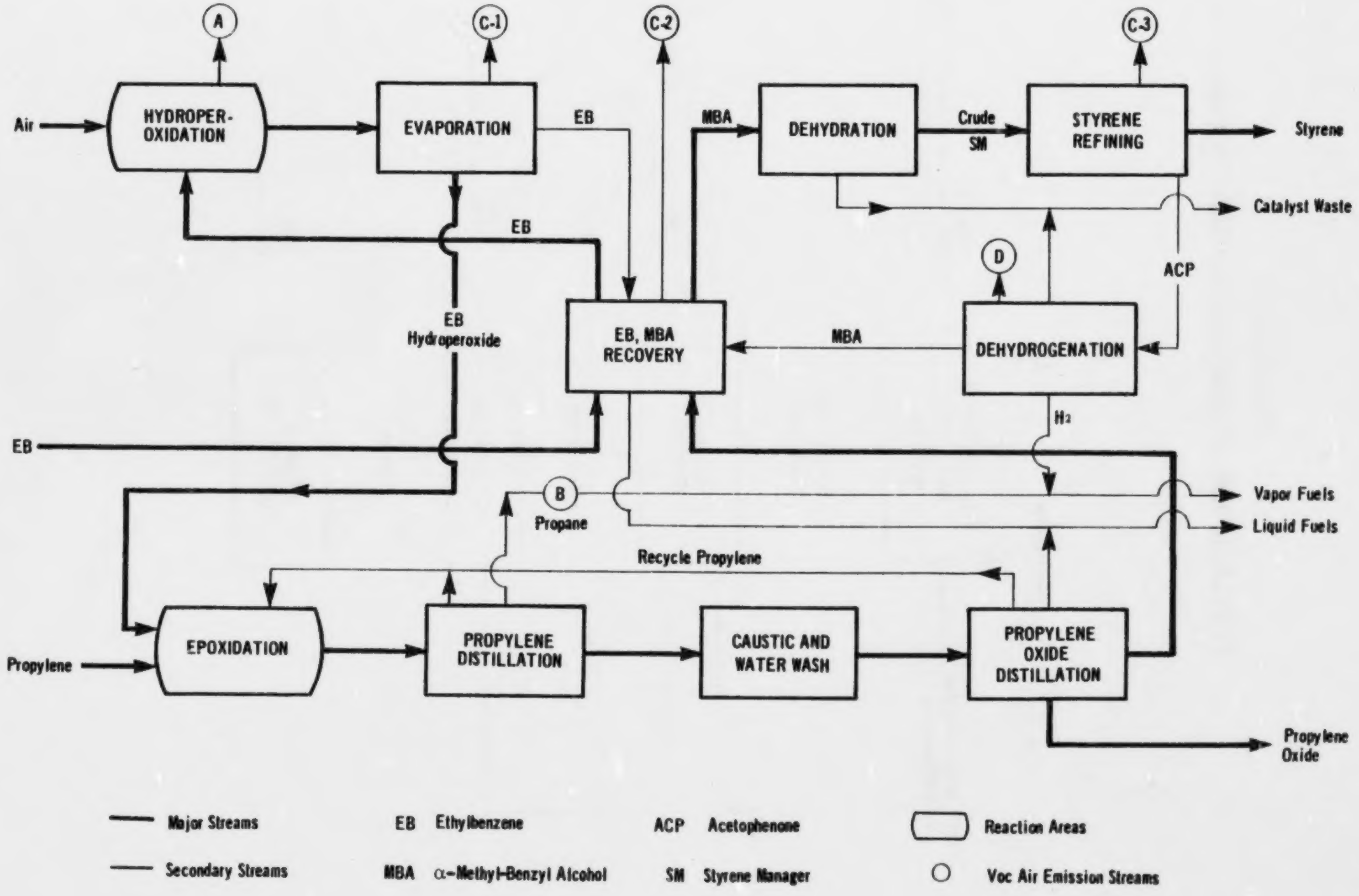
STEP 2
Epoxidation of propylene with ethylbenzene hydroperoxide to propylene oxide and acetophenone

STEP 3
Dehydration of acetophenone and α-methyl-benzyl alcohol to styrene

STEP 4
Purification of styrene

FIGURE 3–9

ETHYLBENZENE HYDROPEROXIDATION PROCESS
BLOCK DIAGRAM



A
C-1
C-2
C-3
Air
HYDROPER-OXIDATION
EVAPORATION
EB
MBA
DEHYDRATION
Crude SM
STYRENE REFINING
Styrene
Catalyst Waste
EB
D
ACP
EB Hydroperoxide
EB, MBA RECOVERY
MBA
DEHYDROGENATION
H_2
EB
B
Propane
Vapor Fuels
Liquid Fuels
Recycle Propylene
Propylene
EPOXIDATION
PROPYLENE DISTILLATION
CAUSTIC AND WATER WASH
PROPYLENE OXIDE DISTILLATION
Propylene Oxide
Major Streams
Secondary Streams
EB Ethylbenzene
MBA α–Methyl-Benzyl Alcohol
ACP Acetophenone
SM Styrene Manager
Reaction Areas
Voc Air Emission Streams

washing with a caustic water salt. The washed epoxidate stream then is distilled to separate the propylene oxide product and to purify the crude propylene oxide from this distillation section. Recovered propylene is recycled to the epoxidation process; residual water is returned to the epoxidate washing operation; and residual liquid impurities are collected in a fuel tank and fed to the process furnace for disposal. The purified propylene oxide is sent to storage tanks prior to shipping.

The organic layer remaining after propylene oxide removal goes to the ethylbenzene, a-methyl-benzyl alcohol recovery operation. In the recovery section, the organic layer again is washed in caustic and water and then distilled. The distillation removes any remaining ethylbenzene and then separates organic waste streams from the a-methyl-benzyl alcohol and acetophenone. The recovered ethylbenzene, along with ethylbenzene from other parts of the process and fresh ethylbenzene, is treated prior to use in the oxidation reactors and the organic waste liquids are stored and used as fuel.

(c) Step 3 -- Dehydration of Acetophenone and A-Methyl-Benzyl Alcohol. The mixed stream of a-methyl-benzyl alcohol and acetophenone from the ethylbenzene recovery section then is dehydrated over a solid catalyst to produce styrene. The residual catalyst solids and high-boiling impurities are separated from the organic product stream and collected for disposal.

(d) Step 4 -- Styrene Purification. The crude styrene goes to a series of vacuum distillation columns where pure styrene monomer is separated and recovered for sale.

After the pure styrene monomer is removed, the residual organic stream contains crude acetophenone, along with a mixture of various impurities. A solid catalyst is dispersed in this crude acetophenone stream. The mixture then is treated under pressure with hydrogen gas to convert the acetophenone to a-methyl-benzyl alcohol. The residual hydrogen stream containing some organic vapors is injected into the waste vapor fuel manifold for combustion in the process furnace. The solid catalyst is activated by treating with hydrogen in a nitrogen medium. The solid catalyst is separated from the crude a-methyl-benzyl stream and is sent to an intermediate storage area. The crude a-methyl-benzyl alcohol from the hydrogenation section is returned to the ethylbenzene, a-methyl-benzyl alcohol recovery section for separation into its useful components.

3.4 EMISSIONS

The primary process sources of benzene and volatile organic chemical (VOC) emissions for the four EB/S processes are described below.

3.4.1 Benzene Alkylation/Ethylbenzene Dehydrogenation

These two processes are discussed together because they represent the typical EB/S production process. Table 3-4 shows the VOC and benzene emissions for a typical plant. This plant uses the process described in Section 3.3.1 and shown in Figures 3-3 and 3-4 and has a capacity of 300,000 Mg/yr (330,000 tons) and an ethylbenzene capacity of 345,000 Mg/yr (380,000 tons).

The four process emission sources in a typical EB/S plant are (1) the alkylation reactor area vents, (2) the atmospheric and pressure column vents, (3) the vacuum column vents, and (4) the hydrogen separation vent. The emission rates for these sources are shown in Table 3-4 along with a national emission estimate and typical compositions and flows. The first three process vent streams are mainly low-flow, high-concentration streams, whereas the hydrogen separation stream is a high-flow, low-concentration stream. Fugitive and storage emissions from EB/S production are not discussed in this document. These emissions will be regulated under separate standards.

The emissions in Table 3-4 are for an integrated plant producing both ethylbenzene and styrene. For plants producing ethylbenzene only, the emissions can be estimated by summing the reactor area and atmospheric and pressure column vent emissions. For plants producing styrene only, the emissions are estimated by summing the vacuum column vent and hydrogen separation vent emissions.

3.4.1.1 Alkylation Reactor Area Vents

Reactor area vents remove various inerts plus entrained aromatics (benzene) from the benzene alkylation reactor. These inerts include nitrogen or methane used in pressure control, unreacted ethylene, reaction by-products, and impurities in the ethylene feed (ethane, methane, and three- and four-carbon hydrocarbons). In most plants which use the traditional

TABLE 3-4. UNCONTROLLED VOC AND BENZENE EMISSIONS, EB/S PRODUCTION VIA ALKYLATION AND DEHYDROGENATION[a]

	kg/10,000 kg Styrene		300,000 Mg/yr Typical Plant kg/hr		Estimated Total Nationwide Benzene Emissions, Mg/yr[c]
	Benzene	Other VOC	Benzene	Other VOC[b]	
Alkylation Reactor Area Vents	3.0	3.0	11.2	11.2	200
Atmospheric/Pressure Column Vents	12.0	6.0	45.0	22.5	1,200
Vacuum Column Vents					
B/T Column[d]	3.0	1.3	11.2	5.0	500
Other	0.5	0.3	1.8	1.0	100

Vent Stream Characteristics[a]

	Alkyl Reaction Area Vents	Atm/Pressure Column Vents	Vacuum Column Vents		Hydrogen Separation Vent
			B/T[d]	Other	
Total					
kg/hr	112	100	25	11.2	6,700
liters/hr at STP	100,000	60,000	15,000	10,000	14×10^6
Weight %					
Benzene	10	45	45	15	6
Other Aromatics	-	5	5	5	30
C_1	32	12	12	30	
C_2/C_5	10	20	20	5	2
Inerts[e]	48	18	18	45	62
kg/hr					
Benzene	11.2	45	11.2	1.7	
Total Combustible VOC	58.0	82	20.0	7.0	

---

[a] The figures are significant to one figure at best. More than one digit is shown in cases to keep the proper ratios between the various vent streams and between the kg/10,000 kg and kg/hr typical plant figures.

[b] Other VOC does not include benzene, ethane, and methane.

[c] Nationwide benzene emissions from the EB/S industry factoring in current levels of control and current production levels.

[d] Benzene/toluene removal column.

[e] Inerts are all other compounds except combustible VOC and include H_2, CO, CO_2, N_2, O_2, and so on.

liquid phase aluminum chloride ($AlCl_3$) catalyst, high purity ethylene is used; therefore, inerts other than those from the ethylene feed are important in creating the vent streams. Before release, the vent streams typically are cooled and then scrubbed with polyethylbenzene, water, or both to recover aromatics.

In contrast to plants using $AlCl_3$ catalyst, plants using the newer solid support catalysts of the UOP or Mobil/Badger process generally employ low-purity ethylene. The resulting reactor vent flows are very large and process economics require the vent gases to be used as fuel. Thus, although these vent gases can be considered potential emissions, they are never vented in practice.

3.4.1.2 Atmospheric and Pressure Column Vents

These column vents mainly remove non-combustibles dissolved in the column feeds, light straight-chain hydrocarbons not released in the reaction area, and any entrained aromatics. The benzene drying column vent also removes any low-boiling impurities in the benzene feed. Most of the emissions occur from the first column in the distillation train, since most of the compounds generating vent streams would be vented in this column.

3.4.1.3 Vacuum Column Vents

The vacuum column vents remove air that leaks into the column, light hydrocarbons and hydrogen formed in dehydrogenation, non-combustibles dissolved in the column feed, and any entrained aromatics. The vacuum columns typically are used in the three distillation steps in styrene purification and in the last distillation step in ethylbenzene purification. As with atmospheric and pressure columns, most of the emissions from vacuum columns would come from the first column in the distillation train.

3.4.1.4 Hydrogen Separation

The hydrogen-rich gas stream from the separator, following the dehydrogenation reaction, consists of hydrogen, methane, ethane, ethylene, carbon dioxide, carbon monoxide, and aromatics formed in the dehydrogenation reactor. In normal operation this stream is cooled and compressed to recover aromatics, rather than vented, and the remaining hydrogen-rich gas is sent to the steam superheater as fuel. This stream is vented directly to the atmosphere or to a flare during plant startup and shutdown and outages of the vent gas compressor in the recovery section and during startup and shutdown. For this report, the hydrogen separation stream under normal conditions is considered an emission stream since, at present, one plant vents this stream to a flare. In view of the uncertainties in flare control efficiencies (Section 4.3), the practice potentially results in high benzene emissions.

Although the hydrogen separation stream is classified as an emission stream, most plants presently burn the stream as fuel because of its high Btu content. Thus, control method, cost, and impact analyses were not performed since the effect on the industry of regulating the stream would be minimal.

3.4.2 Emissions from Ethylbenzene via Mixed Xylenes

Present analysis indicates that ethylbenzene from mixed xylenes emits no benzene because all benzene would likely be removed prior to ethylbenzene extraction (see Figure 3-6). Furthermore, no new benzene emissions would be created in reforming or pyrolysis gasoline production since existing pyrolysis gasoline capacity would provide sufficient ethylbenzene to meet demand. Thus, expansion of these units, with the potential for new benzene emissions, is not required.

The above analysis assumes (1) that producers would not isomerize mixed xylenes to ethylbenzene, but only extract the ethylbenzene already present in the mixed xylenes, and (2) that producers would not transalkylate toluene to mixed xylenes for ethylbenzene. Both of these processes can produce benzene emissions. The above conditions were assumed since extensive analysis would be required to predict the degree of use of these processes. Since preliminary study of ethylbenzene via mixed xylenes showed that this process was not a viable control method (Section 4.6), this extensive analysis was not done.

3.4.3 Emissions from Styrene via Ethylbenzene Hydroperoxidation

This section discusses emissions from the ethylbenzene hydroperoxidation process. The emission data below are based on the capacity of 545 x 10^3 Mg/yr (600 x 10^3 tons/yr) styrene at the one U.S. plant.

There are three main process emissions sources in the hydroperoxidation process: (1) ethylbenzene oxidation reactor vent, (2) propylene recycle purge vent, and (3) vacuum column vents. Of these three sources, the vacuum column vents are the only large benzene emission point. The benzene present in the vent sources results from benzene impurities in the ethylbenzene feed and minor side reactions. Each source is described further below.

3.4.3.1 Ethylbenzene Oxidation Reactor Vent

This vent releases nitrogen and excess oxygen brought into the process with the reaction air; carbon monoxide, carbone dioxide, and light organics produced in the reaction; and organics entrained in the vent gas. The vent stream has a reported flow of approximately 16.4 m^3/sec (580 ft^3/sec) and contains approximately 4.4 percent by weight aromatics, or 3,400 kg/hr (7,480 lbs/hr).

At the one U.S. plant using this process, the vent gas is scrubbed with oil and water for 99 percent removal of organics. The resulting stream is vented to the air and contains approximately 35 ppm of benzene or 7.2 kg/hr.[19]

3.4.3.2 Propylene Recycle Purge Vent

This vent releases propane, propylene, ethane, and other impurities that accumulate in recycling propylene to the epoxidation reactors. No data are available on the flow and composition of this vent. However, based on process flow diagrams and the use in the process of chemical-grade propylene (up to eight percent propane), the stream is a high-Btu gas representing about 50×10^6 Btu/hr and likely would be used as fuel. Again, based on process flow diagrams, no significant benzene is expected in the vent stream.

3.4.3.3 Vacuum Columns

The ethylbenzene hydroperoxidation process contains numerous vacuum columns and evaporators. The vents from these vacuum devices release air drawn into the equipment, inerts and light organics dissolved in the column feeds, nitrogen used for process control, and entrained aromatics. The combined vacuum device vents have a reported flow of 1.0×10^6 liters/hr and contain approximately two percent by weight benzene, or about 27 kg/hr (59 lb/hr). These small quantities of benzene present in the process accumulate at the top of the columns and, due to their high volatility, are drawn out through the vents.

3.4.4 Baseline Emissions

Benzene and VOC emission rates assigned to the uncontrolled model plant were derived from test data collected both by EPA and by plant personnel at existing EB/S facilities. Variations in emissions potential among plants were averaged, assuming a constant capacity, to yield a "typical" emission rate for each vent or group of vents in a plant. Vent stream composition was measured similarly using test data collected at existing plants.

Total nationwide benzene emissions were estimated using the uncontrolled model plant emission rates, which were scaled for both current production levels and benzene control equipment at each plant. In plants where only ethylbenzene or styrene alone is produced, the corresponding process area vents of the model plant were used in estimating the contribution of that source.

3.5 REFERENCES FOR CHAPTER 3

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4. CONTROLS

This chapter describes controls for benzene and VOC emissions in the ethylbenzene/styrene (EB/S) industry and analyzes their efficiencies, advantages, and limitations. The controls are condensation, absorption, flaring, combustion in boilers,* and use of an alternate process. Since new sources should not differ greatly from existing sources, these controls are applicable to both new and existing EB/S plants.

4.1 CONDENSATION

Refrigerated condensers can be used to remove benzene from the vent stream. A complete control system includes the condenser, piping for the vent streams, and refrigerated coolant.

Control of emissions by condensation has several advantages. Condensers are applied easily to the low volume, elevated temperature, saturated vent streams in EB/S plants. They recover benzene and other aromatics as usable products. They do not require new refrigeration and purification equipment since all EB/S plants already have refrigerated brine systems to provide the required coolant (assuming the existing systems have sufficient excess capacity to accommodate the load). Finally, the condensed organics can be routed easily into the production distillation columns for recovery.

The control efficiencies of condensers are determined by the pressure and temperature at which the condenser operates and by the concentration and vapor pressure of the organics in the vent streams. Condensers on EB/S vent streams generally operate at one to three atmospheres and 2 to 5°C on the condenser coils. In addition, they would be applied to streams at 70 to 100 percent saturation in benzene at 40 to 50°C. Condensers under such conditions would achieve 80 to 90 percent reduction of benzene.

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*"Boilers" indicates combustion in any device such as process heaters, superheaters, and other similar units.

A higher efficiency for condensers traditionally can be achieved by increasing pressure and lowering temperatures. However, this is not possible with EB/S plants because of specific pressure and temperature limitations. Higher pressure generally would not be used since compressor costs rise rapidly with increased pressure, while benzene removal efficiency would increase only slowly. Lower temperatures are not possible because the potential exists for the benzene and water in the vent stream to freeze.

The use of condensation is limited by other factors. A condenser cannot handle a short duration, large volume stream resulting from the release of the hydrogen separation vent. Furthermore, although most of the low volume vent streams are saturated, emission streams like those of the alkylation reactor vents and the vacuum column vents in the model plant are not close to saturation with benzene even at 2 to 5°C. Therefore, a system operating at 2 to 5°C and one to three atmospheres would achieve very little control of benzene. Condensation also achieves little control of the two- to five-carbon straight-chain hydrocarbons in the vent streams. At 2 to 5°C, none of the vent streams approaches saturation for any of these compounds.

4.2 ABSORPTION

Another technique for reducing benzene emissions is absorption. In an EB/S plant, an absorption system includes a packed tower and pumps to circulate the scrubbing liquid, a heat exchanger to cool the scrubbing liquid, piping for the vent gases, a brine cooling system, and the scrubbing liquid itself.

Absorption of benzene from an EB/S plant has several advantages. The system could be applied easily. For example, polyethylbenzene (PEB), a mixture of mono-, di-, and triethylbenzene produced during benzene alkylation, is a good benzene solvent. If benzene is absorbed in PEB, the resulting solution can be recycled back to the process and the benzene in solution can be recovered and used as part of the feedstock in the alkylation reactor. Since the PEB is recycled in any case, it would be inexpensive to use as the absorbent and would alleviate the need for special scrubbing liquid or absorbate recovery. An additional advantage for benzene absorption at EB/S plants is that no new refrigeration equipment would be required since all EB/S plants already have refrigerated brine systems providing coolant (assuming the existing systems have sufficient excess capacity to accommodate the load).

The main disadvantages of an absorption system are that (1) it is unsuitable for handling high volume, intermittent releases of gases, and (2) absorbers also produce a pressure drop in the gas stream as it passes through the towers. The use of additional ejectors or the use of packed towers instead of plate or tray towers, however, can compensate for the loss of pressure.

Absorption systems are capable of maintaining good benzene removal efficiencies (between 80 and 99 percent) with vent streams both saturated and unsaturated with benzene. The removal efficiency achieved for a particular absorber and a given solvent is a function of gas composition, solvent temperature, flow rate, tower height and diameter, and the nature of the packing material; removal efficiency increases with tower height and solvent flow rate.

4.3 FLARING

Various vent streams can be manifolded to a flare for thermal destruction. The flare system includes the manifold piping from the vents, an oxygen monitoring system to warn of possible explosive concentrations in the manifold piping, and a flare. The system also includes a knockout drum to remove liquid from the vent gases, a water seal, a flare tip flame retention ring, and the necessary controls to provide for automatic ignition and steam application.

The main advantage of the flare is its ability to control streams and compounds for which condensation or absorption are not applicable. For example, flares can control upset releases and streams such as the alkylation vents which are not saturated in aromatics. In addition, flares can control the light straight-chain hydrocarbons (VOC) in EB/S vent gases not controllable by condensation or absorption.

The major technical difficulties with flares occur in manifolding. As noted in Section 4.5, designs and equipment exist to overcome these difficulties.

Various factors affect flare combustion efficiency, but the chief one is the thoroughness with which flare exit gases are mixed with air. The key design variables affecting mixing are as follows:

- Flare tip diameter -- As flare diameter increases, the turbulence required to mix air thoroughly with all exit gases becomes harder to achieve.
- Exit velocity -- The kinetic energy of the exit gases is important to mixing; that is, the greater the velocity, the more complete the mixing, until a maximum is reached when the flame blows out or the noise becomes unacceptable.
- Steam injection -- Injecting steam also adds kinetic energy to improve mixing and entrains large amounts of air. Increased steam improves mixing until a point is reached where the quenching by the steam and the excess air begins to decrease combustion efficiency.

Furthermore, the presence of saturated organics or aromatic compounds may decrease efficiency since such compounds tend to be thermally stable. Also, if nitrogen is used for pressure control or continuous purging, or if vent streams contain large volumes of compounds with low heats of combustion or non-combustibles, flare combustion may be affected with a decrease in combustion efficiency.

At present, no conclusive data are available on flare efficiency. Calculations and limited test data show benzene destruction efficiencies ranging from 60 to 99 percent. These include engineering evaluations by Hydroscience, Inc.,[1,2] calculations based on residence time,[3] limited and unverified test data on a flare burning methane from a flare manufacturer,[4] and EPA in-house estimates.

For the purposes of this study, a 60 percent destruction efficiency of benzene in flares will be used. This efficiency was chosen because many existing flares in the EB/S industry are not of optimum design. There are large diameter flares designed to handle emergency releases being used to control the low volume, continuous EB/S vent gases. With such designs, optimum mixing is not achieved since the vent gas exit velocity is low and large flares generally cannot inject steam into low volume streams properly. Second, benzene is a stable ring compound requiring longer residence time for combustion than straight-chain organics. Flares which are not optimally designed do not provide extended residence times and thus are judged incapable of achieving high benzene destruction. Until better flare efficiency data are available, a conservative estimate of flare efficiency is necessary.

4.4 BOILERS

Vent streams can be ducted to the burner of a boiler. This control system would use existing EB/S boilers retrofitted appropriately to accept the vent streams.

The boiler control system can be retrofitted in two ways. In the first, lower pressure vents first are compressed and then piped along with higher pressure vents into the boiler fuel header and burned with the regular fuel. In the second, one or several burners in the boiler are replaced by forced draft burners capable of accepting low pressure streams. Streams from the lower pressure vents then are piped to the replacement burners for destruction and from the higher pressure vents to the fuel header or replacement burners. Forced draft burners applicable to this second method are available as standard items for fuel pressures down to one inch of water gauge.[5,6]

A chief advantage of boiler combustion over conventional incineration is that mixing of the waste stream with fuel prior to introduction to the combustion device results in the passage of that gas mixture directly through the burner ports and along the entire flame zone. In this way, optimum gas/air mixing in a controlled environment exposes the benzene to temperatures of 3,000°F. Literature sources indicate that a marked shift occurs both in the mechanism and speed of combustion under these conditions.[7,8,9] Since combustion occurs in only fractions of a second and essentially is complete by the time the gas exits the flame zone, conventional combustion efficiency parameters, such as firebox temperature and residence time, are not critical to this design.

Two other advantages of boilers are energy savings and ease of installation. Energy is saved by recovering the Btu content of the vent streams as steam or process heat. Installation is simple because EB/S plants already require boilers as part of the process and, since the vent streams are combustible, only minor retrofit is required for the boiler to accept these streams.

The major technical problems with the boilers are the same as with flares, i.e., manifolding.

4.5 MANIFOLDING

This section discusses the difficulties of flare and boiler manifolding and describes the designs and equipment available to overcome them. Two problems may be present in manifolding vent streams to boilers and flares: (1) pressure differences in the vent streams, and (2) potential explosion hazards.

In the first area, certain vent or process streams may be at higher pressure than others; thus, if these streams are ducted together, backflow in the vent system may occur. Such backflow can result in off-specification product by introducing impurities in the vent streams into the process or by upsetting process conditions. For example, during outages of the hydrogen offgas compressor, the temporary high pressure in the flare header may place too high a back pressure on steam ejectors tied to the header and upset the vacuum columns.

In the second area, potential explosion hazards may result from ducting vacuum sources to either a flare or boiler. If a leak occurs in the equipment under vacuum, air could be drawn into the system venting a potentially explosive mixture to a combustion source.

Designs and equipment to overcome both problems have been demonstrated and are straightforward to apply. For backflow, two solutions are present:

(1) segregating the low pressure sources, or (2) installing equipment to increase the pressure. The first solution avoids pressure differentials by routing high pressure and low pressure sources differently. At one plant, a separate header for emergency releases is used to prevent any temporary back pressure on other process vessels.[10] At two other plants, a separate header and flare are used specifically for the low pressure vacuum column vents.[11,12] The second solution is to install equipment to increase the pressure of vent streams, either a compressor or an extra ejector stage. Two plants have installed a compressor[13,14] and two others are installing or have installed ejectors driven by natural gas to increase vent stream pressure.[15,16]

For explosion hazards, a number of designs are available. One design uses oxygen analyzers which divert the vent streams to a flare or add inerts if higher oxygen levels are detected. Three plants have such a system.[17,18,19] Other designs include welded pipe to prevent air infiltration, orifices to restrict flow from vacuum equipment in case of leaks, and flame arrestors.[20,21] In addition, some minor process changes may be required to reduce the explosion potential. For example, several plants use steel-covered concrete hotwells for the collection of condensate from steam ejectors. Since these hotwells are prone to air leaks, they would need to be replaced by steel drums or other equipment when ducting the hotwell vents to a combustion source. Alternatively, the steam ejectors could be replaced by a vacuum pump which would do away with the need for a hotwell.

The ability to overcome explosion hazards is demonstrated further by the number of plants that have tied vacuum sources to either a boiler or flare. Three plants have ducted vacuum columns to a flare[22,23,24] and three others to a boiler.[25,26,27] In addition, the basic design of the process at several plants ties a vacuum condensate stripper into the hydrogen-rich offgas used as fuel from styrene production.[28] Finally, a number of plants can operate their dehydrogenators under vacuum; the hydrogen offgas from this step is used as a fuel.[29,30,31]

There should be no manifolding problems associated with an add-on absorption system as a control device.

4.6 ALTERNATE PROCESSES

One final control technique in reducing EB/S benzene emissions is to produce ethylbenzene from mixed xylenes instead of benzene. If this process were used more widely, benzene now extracted from reformate and purified for alkylation to ethylbenzene would be sent directly to gasoline blending. Mixed xylenes now blended into gasoline as part of reformate streams would be extracted from reformate and processed for ethylbenzene.

Technological problems limit the application of this technique in both existing and new plants. Existing EB/S units are of radically different designs and capacities than those required for mixed xylene extraction. If the substitute control technique were applied to existing plants, substituting units of mixed xylenes for units of benzene would be required. However, design and capacity problems limit this. First, most existing benzene, ethylbenzene, and styrene processing equipment is of improper type, configuration, and sequence for mixed xylenes. Mixed xylene extraction is a distillation process, whereas benzene alkylation is a chemical reaction process. The equipment would have to be changed and large parts of the present units scrapped. In most cases, building new mixed xylene units would be simpler. Second, in addition to design limitations, capacity problems exist. Major expansion of aromatics processing capacity would be required to apply this technique to existing plants since the production of one unit of ethylbenzene would require more mixed xylene than it would benzene. The same capacity and design limitations do not apply to new plants; however, for new plants, the special feedstocks and low-cost energy required for producing ethylbenzene from mixed xylenes generally would not be available.

In addition to the design and capacity problems which exist with ethylbenzene extraction from mixed xylenes, benzene emission concerns also exist. As noted in Section 3.4.2, ethylbenzene from mixed xylenes is not being examined as a benzene emission source since the actual separation of ethylbenzene has no benzene emissions. However, as a result of switching ethylbenzene production to extraction from mixed xylenes, benzene emissions may occur.

The analysis of these "global" emissions is complex. Switching processes involves more than substituting one discrete process for another. The switching involves many stages of aromatics processing; each one has benzene emissions which are affected differently.

Switching ethylbenzene processes would likely result in offsetting changes in benzene emissions. First, switching processes would remove large quantities of benzene from benzene alkylation to ethylbenzene. Thus, the process, storage, and fugitive emissions from this process would be eliminated. However, switching processes also would remove large quantities of high octane ethylbenzene from gasoline and the most likely replacement would be the benzene previously alkylated to ethylbenzene. The resulting increase in benzene emissions from gasoline distribution would offset the decrease from the ethylbenzene process. Therefore, switching ethylbenzene production to mixed xylenes is estimated to have no effect on benzene emissions.

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21. Reference 15.

22. Reference 11.

23. Reference 12.

24. Reference 10.

25. Reference 16.

26. Reference 13.

27. Reference 14.

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5. REGULATORY OPTIONS

This chapter discusses the regulatory options considered for controlling continuous benzene emissions resulting from the ethylbenzene/styrene (EB/S) production process and describes the model plant used in assessing the impact of each option.

5.1 MODEL PLANTS

A model plant for the EB/S industry was designed to represent the emissions and control device requirements of a typical EB/S plant. This model plant was used, along with available data on existing plants, to study the plant-by-plant and industry-wide impacts of the regulatory options. Table 5-1 summarizes the characteristics of the model plant used in this study. The criteria for designing the model plant for EB/S are described below.

The preliminary criterion in selecting the EB/S model plant was to consider the number of model plants needed to represent properly the EB/S industry. Several model plants would be needed if the variations existing in EB/S processes, plant size, emissions, etc., lead to widely different impacts on different plants for each regulatory option.

Three major process variations exist: the ethylbenzene hydroperoxidation process, the vapor phase alkylation reaction, and the hydroperoxidation reactor. Though the ethylbenzene hydroperoxidation process differs from the ethylbenzene dehydrogenation process, its main benzene emission point, the vacuum column, is the same. Thus, the control methods and costs for the ethylbenzene dehydrogenation process are applicable to hydroperoxidation. Vapor phase alkylation can use dilute ethylene which can result in a much greater vent flow than the model plant. However, due to the high flow and Btu content of the offgas from vapor phase alkylation using dilute ethylene, plants currently using this process burn the stream; therefore, this variation would not affect the regulatory analysis. Emissions from the hydroperoxidation reactor differ widely from emissions from the ethylbenzene dehydrogenation process. However, only one reactor is used domestically and its emissions, controls, and control costs can be studied without using a model plant. Therefore, rather than designing a second model plant solely for analyzing the potentially different impacts from the one hydroperoxidation reactor vent, a separate study of this emission point was completed and is presented in the Addendum to this document. Because none of these variations would affect the regulatory analysis, all impacts were studied by scaling or modifying one model plant. Variations in plant size and levels of control were scaled according to the model plant parameters. Variations in emissions resulted in only small changes in cost and no change in applicable control technology.

Because there are no technological reasons to consider different or alternative models for new or existing plants, one model plant was considered representative of both.

The hydrogen separation stream typically is classified as an emission stream. However, control method, cost, and impact analyses were not performed for this stream since most plants currently burn it as fuel because of its high Btu content. This variation has minimal impact on the regulatory analysis.

The second criterion in selecting the model plant was to determine the specific process, emissions, and other characteristics of the model plant. This was done by conducting EPA field surveys, tests, and literature searches.

TABLE 5-1. EB/S MODEL PLANT

1. Process/Capacity	The model plant is an integrated ethylbenzene/styrene unit using the benzene alkylation and ethylbenzene dehydrogenation processes outlined in Section 3.3.1. The capacity is 345,000 Mg/yr for ethylbenzene and 300,000 Mg/yr for styrene based on 8,000 hrs/yr of operation.
2. Vent Streams	The vent points for the model plant are described in Section 3.4.1 and the vent flows and composition are listed in Table 3-4.
3. Energy Wastewater Load	The energy use for steam, process heat, electricity, etc. at the model plant is approximately 5,000 kJ/kg styrene. The wastewater load is 50 to 3,000 gallons per 1,000 lbs and the TOC content is 0.2 to 40 lbs per 1,000 lbs.
4. Baseline Controls	The model plant assumes that the hydrogen separation vent is processed for aromatics recovery and then burned in the styrene superheater. In the same model plant, vents are uncontrolled. However, in the plant-by-plant cost analysis, the remaining vents are controlled to the degree present at each existing plant.
5. Location/Size	The model plant is located in an integrated chemical complex sharing utilities, storage, and similar services with other units in the complex. The dimensions of the EB/S unit and entire complex are shown in Figure 6-1.

The values of the model plant then were determined by interpreting and averaging these data in light of basic engineering principles and EPA experience with the EB/S industry.

5.2 REGULATORY OPTIONS

The regulatory options considered for controlling EB/S benzene emissions are based on application of benzene emission controls, or combination of controls, discussed in detail in Chapter 4 and summarized, along with respective control efficiencies, in Table 5-2. Some of these control techniques, however, were not considered in developing the regulatory options because of specific limitations in their use or application.

The Administrator has been reluctant to allow the use of flares as a continuous process emission control device because emissions cannot be measured practically to determine if the flares are in compliance. Furthermore, due to their relatively low or variable efficiency, the Administrator does not consider flares as a single, effective control technique for continuous process benzene emissions.

Condensation alone cannot control all vent streams, such as short duration, large volume streams or low volume, unsaturated streams. Absorption alone cannot handle high volume, intermittent releases of gases. Because of these limitations, these control devices were rejected as single, effective benzene emissions controls.

However, a combination of condensers (achieving 80 to 90 percent efficiency) on the vents saturated with benzene and absorption towers (achieving 80 to 99 percent efficiency) on the vents not saturated with benzene can provide an overall benzene control efficiency of 85 percent. In conjunction with condensation and absorption, flaring can control the large volume, intermittent releases for which condensation or absorption is not applicable,

TABLE 5-2. SUMMARY OF CONTROLS

Control	Application/Limitation	Benzene Control Efficiency
PRODUCT RECOVERY		
1) Condensation	Good control efficiency for saturated process vent streams.	80-90%
2) Absorption	Best suited for dilute process vent streams. Potentially high control efficiency.	80-99%
COMBUSTION		
1) Flaring	Low and/or variable destruction efficiency.	60-99%
2) Incineration	High control efficiency for all process streams.	99%
3) Routing of Waste Streams to Boiler	High control efficiency for all process streams.	99%
PROCESS MODIFICATION		
1) Production of Ethylbenzene from Mixed Xylenes	Would require manufacture of ethylbenzene from mixed xylenes (a distillation process) and major equipment changes.	100%[a]
SUBSTITUTE FOR STYRENE	Would require manufacture of substitute and/or importation of styrene from foreign sources. Assumes plant closure.	100%

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[a] However, as a result of switching ethylbenzene production to extraction from mixed xylenes, benzene emissions from other sources, such as associated refinery operations and gasoline distribution, may increase with ultimately no reduction in nationwide benzene emissions from all sources.

achieving an overall benzene destruction efficiency of 94 percent. These combinations of equipment were considered in developing the regulatory option.

Although EB/S plants could modify their processes and produce ethylbenzene from mixed xylenes instead of benzene, the Administrator does not consider this process modification as a viable regulatory option. The actual separation of ethylbenzene from mixed xylenes has no emissions. However, as a result of switching ethylbenzene production to extraction from mixed xylenes, benzene emissions from other sources, such as associated refinery operations and gasoline distribution, may increase with ultimately no reduction in nationwide benzene emissions from all sources.

A retrofitted boiler, process heater, or superheater can achieve a high, but varying, degree of control depending on the inlet level of benzene. Based on the range of inlet at existing EB/S plants, these control devices can achieve approximately 99 percent destruction efficiency and therefore were considered as single, effective control devices in developing the regulatory options. A combination of condensers, absorption towers, and boilers,* however, cannot achieve any greater reduction in emissions than boilers alone because the condenser and absorption tower reduce the inlet concentrations and, as a result, the boiler operates at a lower destruction efficiency than if it were receiving concentrated, uncontrolled inlet. This combination of equipment was not considered in developing the regulatory options because it is no more effective in reducing benzene emissions than a single boiler.

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*Boilers also include process heaters, superheaters, and other similar units.

Based on these considerations, the Administrator therefore is considering five regulatory options for controlling benzene emissions from EB/S plants:

- Do not set a standard.
- Regulatory Option A: Require that EB/S plants achieve 85 percent benzene emissions reduction in the main process vents. This alternative is based on condensers for some main process vents and absorbers for others.
- Regulatory Option B: Require that EB/S plants achieve a 94 percent benzene emissions reduction in the main process vents. This alternative is based on using condensers for some main process vents and absorbers for others followed by a flare.
- Regulatory Option C: Require that EB/S plants achieve 99 percent benzene emissions reduction in the main process vents. This alternative is based on the use of a boiler for controlling the main process vents.
- Regulatory Option D: Require that EB/S plants achieve 100 percent reduction in benzene emissions. This alternative is based on the use of substitutes for styrene and assumes that all EB/S plants will be forced to close.

Under all options, all continuous releases from the hydrogen separation vent would be required to achieve 99 percent control. We believe this to be possible based on the current industry practice of sending the hydrogen-rich gas stream to the steam superheater.

6. ENVIRONMENTAL AND ENERGY IMPACTS

This chapter discusses the environmental and energy impacts of each regulatory option presented in Chapter 5. Impacts are discussed with regard to air quality, water quality, solid waste, and energy requirements. Both beneficial and adverse effects are presented, the major emphasis being on the incremental impact of the regulatory options.

Five regulatory options are considered in the ethylbenzene/styrene (EB/S) analysis, including not setting a standard. Four of these options involve limiting benzene emissions from the process vents, consisting of the alkylation reaction vents, the atmospheric pressure column vents, and the vacuum column vents. Process vent emissions also include the continuous release of the hydrogen separation section.

With regard to these source categories, five basic regulatory options were considered and three of these were analyzed:

- Do not set a Standard -- This option assumes that current levels of benzene emissions from process vents are controlled adequately to protect public health. EB/S benzene emissions are controlled to some extent via State Implementation Plans (SIP) hydrocarbon emission regulations.

- Regulatory Option A (85 percent control) -- A benzene emission control efficiency of 85 percent is achieved by routing process streams to a scrubber or condenser system. The scrubber is sized to control continuous venting from the alkylation reactor and all vacuum columns in the EB/S facility with the exception of the benzene/toluene columns. The condenser system controls releases from the benzene/toluene hotwell vents and from all columns operating at atmospheric pressure and above. The continuous release of the hydrogen separation vent is routed to a boiler* after primary product recovery (60 percent benzene recovery) to achieve an overall benzene emission control of 99 percent.

- Regulatory Option B (94 percent control) -- A benzene emission control efficiency of 94 percent is achieved by coupling a flare system to the scrubber/condenser system of Regulatory Option A. All process streams are first handled as in Regulatory Option A; the vent streams from the scrubber and condenser subsequently are manifolded into a flare system sized to handle the continuous vent releases. Emissions from the hydrogen separation section also are treated as in Regulatory Option A.

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*Boilers include process heaters, superheaters, and other similar units.

- Regulatory Option C (99 percent control) -- Under this regulatory option, all process vent streams are manifolded together and subsequently routed to an existing boiler to achieve a benzene control efficiency of 99 percent. Emissions from the separation section are treated as in Regulatory Option A.
- Regulatory Option D (100 percent control) -- This regulatory option entails 100 percent benzene emission control via plant closure and substitutes for styrene.

Each level of control was analyzed with respect to a model plant of 300,000 Mg/yr styrene capacity; where applicable, plant-by-plant impacts at existing facilities were analyzed and presented. (The fifth regulatory option of 100 percent control involves closure of the industry and therefore is discussed on an industry-wide rather than a model plant basis. The discussion of this option is presented in Chapter 7.)

6.1 AIR IMPACTS

Air quality impacts were analyzed through the use of the Industrial Source Complex (ISC) dispersion model.[1] ISC predicts the ambient concentrations that would result from air pollutant sources based on meteorological data and the characteristics of the emitting sources (such as emission rate, stack height, and stack gas temperature). The three regulatory options (A, B, and C) and one uncontrolled scenario were examined. Appendix B contains a discussion of the overall modeling methodology.

A 300,000 Mg/yr styrene production capacity model plant was used as the basis for this analysis. Figure 6-1 shows the layout of the model plant and the location of all sources, including fugitive emissions from the EB/S unit, three storage tanks, and the hydrogen separation vent.* Figure 6-2

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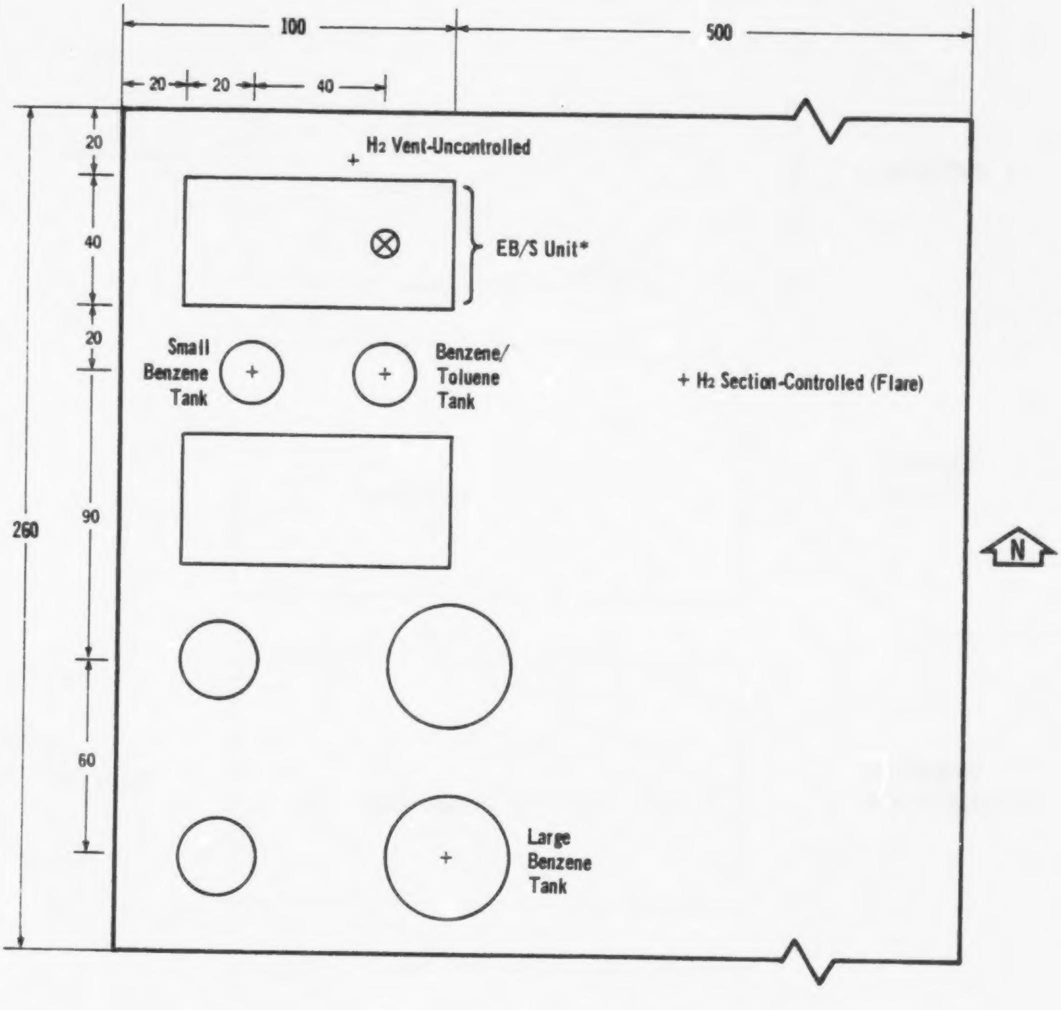
*The hydrogen separation vent emissions are discussed in the Addendum on Excess Emissions.

FIGURE 6-1
MODEL PLANT LAYOUT


100
500
20
20
40
20
40
20
90
60
260
H2 Vent-Uncontrolled
EB/S Unit*
Small Benzene Tank
Benzene/ Toluene Tank
+ H2 Section-Controlled (Flare)
Large Benzene Tank
N

KEY:

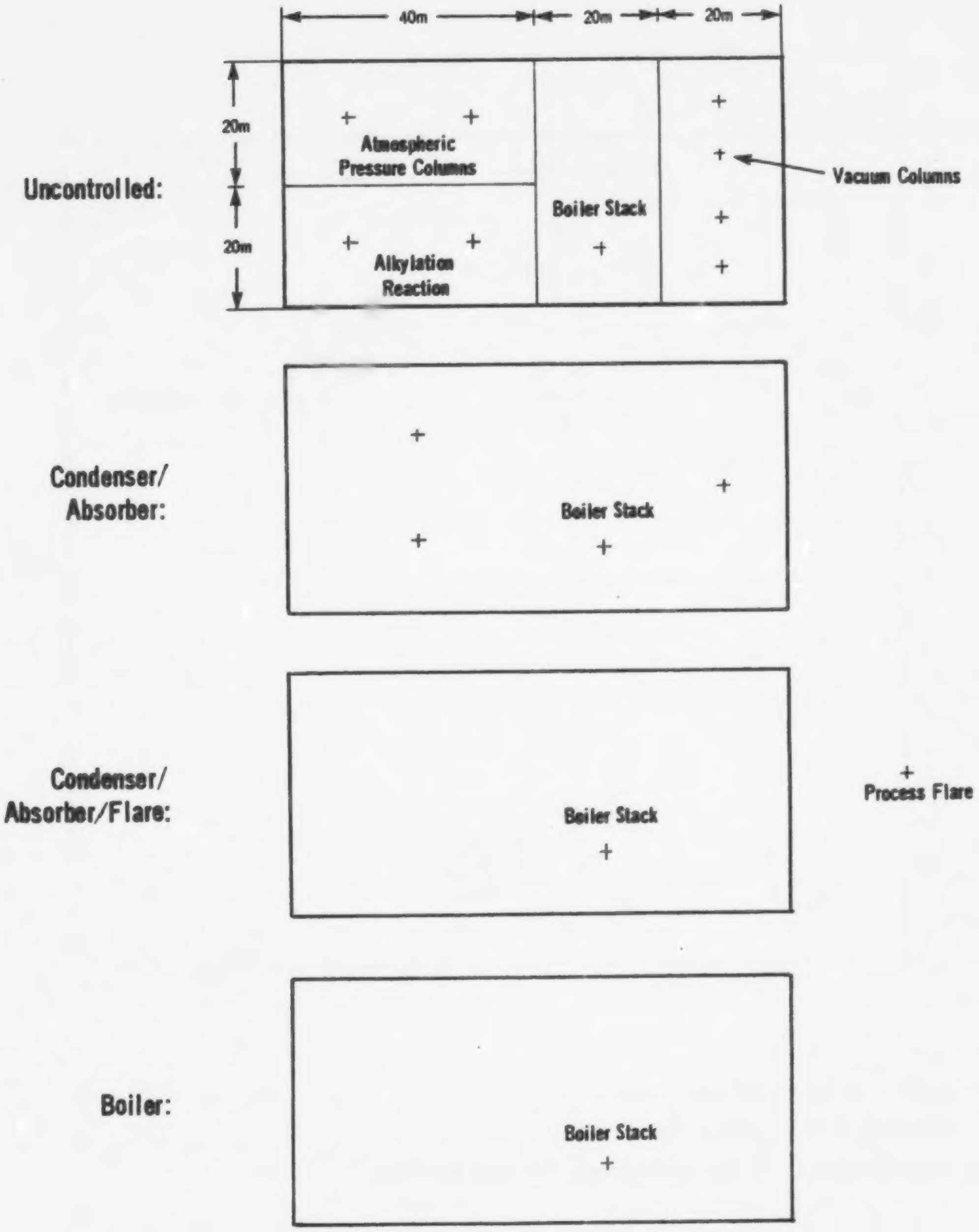
1 cm = 20 Meters, All Numbers are Distances in Meters.

⊗ = Center Point for Dispersion Model Receptor Grid.

* For Fugitive Emissions the EB/S Unit was Modeled as Two Square Area Sources.

FIGURE 6–2

LOCATION OF PROCESS EMISSIONS FOR THE FOUR REGULATORY OPTIONS*


40m
20m
20m
20m
20m
Uncontrolled:
Atmospheric Pressure Columns
Alkylation Reaction
Boiler Stack
Vacuum Columns
Condenser/ Absorber:
Boiler Stack
Condenser/ Absorber/Flare:
Boiler Stack
Process Flare
Boiler:
Boiler Stack

* Large Rectangle Represents the EB/S Unit in Figure 6–1

shows the specific locations of the process emission sources for each of the four regulatory options.

6.1.1 Modeling Results

The results of the dispersion analysis are summarized in Tables 6-1 and 6-2.* Table 6-1 shows the maximum ambient benzene concentration for each regulatory option and for each of the averaging periods considered. These concentrations include uncontrolled fugitive and current control levels for storage emissions. The table also shows the contribution of the process emissions to the total plant annual average impacts. Table 6-2 shows the impacts of the individual sources or groups of sources that comprise the model plant.**

It should be noted that the "uncontrolled" model plant is included in this analysis solely as a basis for comparison and does not reflect current levels of control practiced by the industry. Actual emission levels at existing facilities average about 70 percent less than those assumed for the uncontrolled model plant (based on an overall 70 percent benzene control efficiency). In this respect, current control levels fall somewhere between the uncontrolled case and Regulatory Option A.

Table 6-1 shows high benzene concentrations from the uncontrolled plant, due mostly to process vent emissions. Impacts are considerably lower under Regulatory Option A (condenser/absorber), with process vent emissions accounting for approximately half of total plant impact. For Regulatory Options B (condenser/absorber/flare) and C (boiler), process vent emissions no longer exert the predominant impact. Instead, storage and fugitive emissions account for virtually all of the impact recorded for these latter two regulatory options.

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*Table B-3 in Appendix B gives more detailed modeling results and shows concentrations at various distances from the plant.

**Ambient concentrations in all tables may be converted to ppb by the following relationship: 3.19 $\mu g/m^3$ = 1 ppb.

Combined impacts from all sources under each regulatory option are located near the assumed boundaries of the plant property (160 to 300 meters (m) from the source). For individual emission sources or source groups, the highest estimated maximum annual average concentrations, including emissions, usually occurred at 160 m from the model plant, except in the case of Regulatory Options B and C. Maximum concentrations for process emission points occurred at 500 m and 1,000 m, respectively, from the source. The greater distance is due to the greater buoyancy of the hot plume associated with the flare and boiler source compared to the source characteristics of the other regulatory options.

Table 6-3 depicts estimated maximum annual average benzene concentrations associated with individual existing plants. These estimates are based on the emission rates and pollution control relationships between existing plants and the model plant under each regulatory option. These estimates are useful for comparative purposes only and should not be taken to represent actual conditions since aspects such as individual source characteristics and source locations are not considered.

6.1.2 Effects of Benzene Controls on Nationwide Emissions

Utilization of the condenser/absorption tower system (Regulatory Option A) at all existing facilities would reduce nationwide benzene emissions by 1,365 Mg/yr.* The integrated condenser or absorption tower/flare

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*Estimated total benzene emissions from process vents alone in the EB/S industry are approximately 1,990 Mg/yr. Current levels of control and 100 percent capacity are factored in this estimate.

TABLE 6-1. MAXIMUM BENZENE CONCENTRATIONS FROM MODEL PLANT

Option	Total Plant Emission Rate[b] (g/sec)	Combined Maximum Concentration[a] ($\mu g/m^3$)				Contribution of the Process Vents to the Combined Maximum Concentration ($\mu g/m^3$)
		1 hr	8 hr	24 hr	Annual Average	Annual Average
Uncontrolled model plant	22	12,305	3,127	1,541	400	338.0
Regulatory Option A (85%)	4	3,103	992	423	127	65.0
Regulatory Option B (94%)	3	1,846	491	262	63	2.2
Regulatory Option C (99%)	2	1,846	486	262	63	0.1

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[a] All concentrations include emissions from fugitive sources which are assumed uncontrolled and emissions from storage which represent current levels of control.

[b] Maximum hourly emission rate (i.e., one hour average).

TABLE 6-2. PREDICTED MAXIMUM AMBIENT BENZENE CONCENTRATIONS FOR INDIVIDUAL SOURCES (300,000 Mg/yr Model Plant)

Source or Source Group	Emission Rate[a] (g/sec)	Concentration in $\mu g/m^3$			
		1 hr	8 hr	24 hr	Annual Average
Process Emissions -- Uncontrolled[b]	20.0	11,317	2,777.0	1,350.0	338.0
Process Emissions -- Condenser/Absorption Tower[c]	3.0	1,781	511.0	218.0	65.0
Process Emissions -- Condenser/Absorption Tower/Flare[c]	1.2	45	22.0	7.0	2.0
Process Emissions -- Boiler[d]	0.1	1	0.2	0.1	0.1
Fugitive Sources[b]	0.4	1,016	263.0	121.0	27.0
Storage Tanks[b]	1.5	1,291	393.0	178.0	38.0
Hydrogen Separation Section to Boiler[b]	0.4	3	1.0	1.0	0.3

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[a] Total emission rate is given for each source group. All are maximum hourly emission rates except for the two designated as annual averages.

[b] Maximum occurs at 0.16 km downwind of plant.

[c] Maximum occurs at 0.5 km downwind of plant.

[d] Maximum occurs at 1.0 km downwind of plant.

TABLE 6-3. ESTIMATED AMBIENT IMPACTS FOR SPECIFIC EB/S PLANTS[a]

Plant	Capacity in 10^3 Mg/yr (EB/S)	Maximum Annual Average Concentrations in $\mu g/m^3$			
		Existing Controls	Regulatory Option A (85%)	Regulatory Option B (94%)	Regulatory Option C (99%)
American Hoechst	526/450	305	158	101	101
Amoco	447/380	90	77	75	73
Arco, Penn.	*0[b]/200*	57	21	12	12
Arco, Texas	227/0[b]	214	76	44	44
Cos-Mar	689/590	130	124	124	124
Dow, Texas	847/680	249	169	142	142
Dow, Midland	250/181	47	14	6	6
El Paso	125/108	29	29	28	28
Gulf	313/272	58	56	55	57
Monsanto	771/590	129	129	129	129
Oxirane	545/454	97	96	95	95
Sun Oil	61/36	29	21	18	18
U.S. Steel	61/54	6	6	6	6

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[a] Includes impacts from fugitive and storage, as well as process, emissions. All concentrations were scaled linearly, based on the model plant results. For individual plants, two scaling factors (one for process emissions and one for fugitive and storage emissions) were derived, based on the size relationship of process streams and storage facilities and relative control levels to those of the model plant. The scaling factors do not consider many factors which affect ambient pollutant impact, such as differences in source location and stack parameters (e.g., height) among the various plants. Therefore, these concentrations are useful only to show relative differences among the impacts of various plants, but should not be considered as depicting actual plant impacts.

[b] Ethylbenzene is produced at Arco, TX and transferred to Arco, Kobuta, PA, where polystyrene and styrene-butadiene copolymer are manufactured.

system (Regulatory Option B) would reduce nationwide benzene emissions by 1,790 Mg/yr. Finally, a special burner and controls (Regulatory Option C), retrofitted in an existing boiler, will reduce benzene emissions by 1,920 Mg/yr for the model plant. In this latter option, neither benzene nor other organics are recycled back to the process; however, energy savings are realized by recovering the thermal energy content of the vent streams in the form of steam.

6.2 WATER QUALITY IMPACT AND CONSUMPTION

None of the regulatory options considered results in any significant increase in wastewater discharge by EB/S facilities. No water effluents are discharged from either flares or boilers themselves (Regulatory Options B and C, respectively). A small amount of water is collected from the vapor streams running through the scrubbers and condensers (Regulatory Options A and B). Most of this condensed water can be recycled back to the process, increasing total plant wastewater flows by less than 50 gallons/hour, an amount which would not affect current plant waste treatment capacity.

The net water consumption for the boiler and condenser/absorption systems is zero. The condenser/absorption tower utilizes polyethylbenzene as an absorbent medium which is chilled via a heat exchanger coupled to the plant's brine refrigeration system.

The flares use water in the form of steam which is injected into the combustion zone of the stack. Water consumption for the 300,000 Mg/yr model plant incorporating a three-inch flare is approximately 380 m^3/yr. Water use for the water seal in the base of the flare stack is negligible.

6.3 SOLID WASTE DISPOSAL IMPACT

None of the regulatory options being considered generates solid waste.

6.4 ENERGY IMPACT

Table 6-4 presents the total energy requirements for each control strategy as applied to a 300,000 Mg/yr model plant. For Regulatory Options A and B, energy requirements amount to less than 0.1 percent each of total plant energy requirements; conversely, Regulatory Option C results in an energy credit of less than 0.1 percent of total plant consumption. All energy impacts are essentially linear with respect to plant capacity.

6.4.1 (Option A) 85 Percent Benzene Emission Control

In the condenser and absorber emission control (or product recovery) system, electrical energy is required due to a slight demand on the brine system's cooling load. Electricity is required to operate pumps and compressors. Pumps are required to circulate the refrigerant and absorbent; compressors are required for vacuum vents and other waste streams under negative or extremely low pressure. Total electrical requirements for pumps and compressors are on the order of 60×10^3 MJ/yr for the model plant. Energy demand on the cooling system for condenser operation is approximately 750×10^3 MJ/yr for the model plant.

6.4.2 (Option B) 94 Percent Benzene Emission Control

Flare operation consumes both steam (for smoke control) and natural gas (for pilot and purge requirements). A flare system placed downstream of a condenser/absorption tower system on a 300,000 Mg/yr model plant would consist of a three-inch flare for process vent emissions. Steam consumption for the three-inch flare is approximately 9.4×10^5 MJ/yr. Natural gas consumption for the flare is approximately 1.2×10^6 MJ/yr (natural gas is necessary for both pilot operation and purging the flare of organics). The total energy demand of this regulatory option, including the condenser/absorber system, would be approximately 2.9×10^6 MJ/yr for the model plant. (Electrical energy needs for the oxygen monitoring equipment is negligible.)

6.4.3 (Option C) 99 Percent Benzene Emission Control

In the event a compressor is needed to direct low-pressure vent streams to the burner assembly, electrical energy consumption would be approximately 30×10^3 MJ/yr. Electrical energy used for the oxygen monitoring equipment would be negligible. Assuming a conservative 75 percent heat recovery in the form of steam from combustion of the waste gas streams, an energy credit of approximately 53×10^6 MJ/yr could be attained.

6.4.4 Summary of Energy Impact

Regulatory Option C, at 99 percent benzene control, provides an energy credit of 53×10^6 Mg/yr. This is equivalent to 8,500 barrels of oil. The energy credit, in the form of steam, is derived by assuming 75 percent heat recovery of the combusted waste streams.

The condenser/absorption tower option (A) and the condenser/absorption tower/flare option (B), at 85 and 94 percent benzene control, respectively, provide substantial product recovery capability. Each recovers 613×10^3 Kg of benzene per year (300,000 Mg/yr plant) which is recycled continuously to the alkylation process.

It is difficult to present an accurate estimate of possible national energy requirements due to a standard based on one of the regulatory options. The actual total national energy impact under each regulatory option depends upon both the control technique chosen and the existing level of control for a particular plant. Insufficient data exist to determine the current energy demand of the control equipment present on existing facilities. However, a "worst-case" situation, i.e., completely uncontrolled plants, can be used to estimate the national energy impact for each level of control. Therefore, assuming no energy credits for controls already in place, the

TABLE 6-4. TOTAL NET ENERGY REQUIREMENTS OF REGULATORY OPTIONS FOR 300,000 Mg/YR MODEL PLANT

Total Process Energy Requirements of Model Plant MJ/yr (bbl/yr)[a]	(Option A) 85 Percent Benzene Control Condenser/ Absorption Tower[b] MJ/yr (bbl/yr)	(Option B) 94 Percent Benzene Control Condenser/Absorption Tower/Flare[b] MJ/yr (bbl/yr)	(Option C) 99 Percent Benzene Control Boiler[c] MJ/yr (bbl/yr)
6.9×10^9	810×10^3	$2,910 \times 10^3$	$- 53 \times 10^6$
(1.1×10^6)	(130)	(440)	(8,500)

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[a] Barrels of oil equivalent, assuming 140,000 Btu/gal.

[b] The condenser/absorption tower has a benzene recovery capability of approximately 70 Kg/hr.

[c] Combusting the waste gas, via a low-pressure burner in an existing boiler, produces an energy credit in the form of steam. Assuming 75 percent heat recovery, and an energy requirement of 30×10^3 MJ/yr, annual energy credits amount to 53×10^6 MJ/yr or 8,536 barrels of oil for the 300,000 Mg/yr model plant.

total national energy requirements would be 11.0 x 10^6 MJ/yr or 1,800 bbl/yr of energy under Regulatory Option A; 39.6 x 10^6 MJ/yr or 6,000 bbl/yr under Regulatory Option B; and a savings of 723.0 x 10^6 MJ/yr or 117,000 bbl/yr under Regulatory Option C.

6.5 OTHER ENVIRONMENTAL CONCERNS

6.5.1 Flare Noise

The flaring process and the noise it generates may have an impact on the surrounding environment. Estimated sound pressure levels decibels (dB) of the three-inch flare designed to burn continuous process emissions is approximately 79 dB at the base of the flare stack.* This estimate assumes no steam injection. While the introduction of steam into the combustion zone of the stack increases its destruction efficiency, it may increase overall noise levels of the flare. However, it is believed that the flare can be designed properly to minimize noise.[2] Table 6-5 compares flare noise levels with the Occupational Health and Safety Administration (OSHA) standards[3] and EPA recommendations for noise levels requisite to protect public health and welfare in the industrial environment.[4] Sound pressure level is reduced as a function of distance.[5] At 47 meters, the sound pressure level for the three-inch diameter flare falls to 70 dB.**

6.5.2 Flare Thermal Radiation

Flares also emit thermal radiation. Stack height must be sufficient to ensure the safety of personnel working in the vicinity of the flare. Calculations of thermal radiation intensity indicate that the three-inch diameter flare employed for burning continuous process emissions emits 750

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*Assumes noise originates at center of flame.

**EPA recommendation for maximum dB level to protect against hearing loss (24-hour exposure).

TABLE 6-5. FLARE NOISE LEVEL RELATIVE TO OSHA STANDARDS AND EPA GUIDELINES

Estimated Flare Noise (dB)	Comparative Noise Levels (dB)	
FLARE SIZE 3"	EPA Guideline for Industrial Area[a] (Hearing Loss Consideration for 24-Hour Levels)	OSHA Permissible Noise Exposure[b] (8-Hour Exposure Level)
79	70	90

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[a] Sound levels identified as requisite to protect the public health and welfare with an adequate margin of safety.

[b] Sound level dBA slow response.

Kcal/hr sq m,* which, when added to the maximum ambient solar radiation, amounts to approximately 1,550 Kcal/hr sq m.** The acceptable heat intensity for short-term exposures is 4,000 Kcal/hr sq m (this will harm personnel if skin is exposed for more than a few seconds).[6]

6.6 IRREVERSIBLE AND IRRETRIEVABLE COMMITMENT OF RESOURCES

Regulatory Options A (85 percent control) and B (94 percent control) recover a significant quantity of benzene. Benzene is considered a valuable raw material and is used in many industrial applications. Although Regulatory Option C (99 percent) does not provide recovered benzene as do the other regulatory options, an energy credit from the combusted waste stream may be realized. Both the benzene credit from Regulatory Options A and B and the energy credit from Regulatory Option C can be expressed in terms of the barrels of oil required to produce the benzene or energy. The benzene recovered in Regulatory Options A and B, assuming no current controls, would require 80,000 bbl/yr of oil to produce and the energy recovered under Regulatory Option C would require 117,000 bbl/yr of oil. These figures are small in comparison to the total nationwide oil consumption for all uses. In this respect, the energy credit for each option would be considered approximately the same as would their savings of non-renewable resources.

6.7 ENVIRONMENTAL IMPACT OF DELAYED STANDARDS

In the event that the standard is delayed, significant negative impacts on ambient air quality could result. Projected benzene emissions from plants at current control levels should remain at least an order of magnitude greater than those from plants equipped with the controls under Regulatory Option C. EB/S plants now are operating at less than full capacity but are expected to reach full capacity within five years.[7] Based on current levels of continuous process emissions in relation to those under Regulatory Option C (1,990 Mg/yr and 70 Mg/yr, respectively), an annual growth rate of six percent should increase emission levels linearly.

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*As measured on the ground adjacent to the flare stack -- assuming heat source originates from center of flame.

**The maximum ambient solar radiation ranges up to 800 Kcal/hr sq m at 30 degrees north latitude.

As stated in Sections 6.2 and 6.3, there are no significant water quality or solid waste impacts (positive or negative) associated with the control equipment. Therefore, there are no anticipated impacts in these areas in the event of a delay in the standard.

Although Regulatory Options A and B require energy for their operation and Regulatory Option C results in a small energy savings, each accounts for less than 0.1 percent of total plant energy requirements. Energy impacts, therefore, would be considered negligible in the event of a delay in proposal or promulgation of the standard.

6.8 REFERENCES FOR CHAPTER 6

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7. ECONOMIC IMPACT

This chapter discusses the potential economic impacts of each regulatory option presented in Chapter 5. Impacts on both individual firms and the general economy are considered.

7.1 INDUSTRY ECONOMIC PROFILE

7.1.1 Introduction

Styrene is produced by 11 companies at 12 locations in the United States (Figure 3-2). Ten of these 12 plants are located in Texas and Louisiana. The remaining two plants are the Atlantic Richfield facility at Kobuta, Pennsylvania, and the Dow Chemical facility at Midland, Michigan. Approximately 98 percent of the styrene produced in these two facilities is captively consumed. Consequently, virtually all shipments of styrene originate in the same basic geographic area.

Ethylbenzene (EB) is produced by 14 companies at 15 locations (Figure 3-1). Only one of these plants is located outside Texas or Louisiana: Commonwealth Oil in Penuelas, Puerto Rico. The 11 companies that produce styrene also produce EB. These companies account for more than 97 percent of the U.S. EB capacity.[1]

For the purposes of this analysis, ethylbenzene/styrene (EB/S) is considered a single industry. It has been estimated that 99 percent of the EB produced in the U.S. is used in domestic styrene manufacture. (EB also can be used as a solvent.) In fact, in many integrated EB/S operations, EB is not separated as such.[2] Most EB (90 percent or more) is not sold on the market but is consumed by the producing company.

7.1.2 Product

7.1.2.1 Production

Styrene is a fragrant liquid unsaturated hydrocarbon that is produced from EB. It may be produced as a prime product or as a coproduct with propylene oxide. EB may be produced as a prime product or recovered from mixed xylene streams in refineries. Each of these processes will be discussed separately.

(a) Ethylbenzene: benzene alkylation. The predominant production process for EB is the alkylation of benzene with ethylene. In 1978, 97.8 percent of total EB capacity was based on benzene alkylation.[1] From 1965 to 1975, the percentage of EB produced through alkylation increased from 88.6 percent to 97.4 percent.[2,3] It is anticipated that this percentage will be maintained or even increased in the future (see mixed xylene extraction, below). As shown in Table 7-1, 11 of the 14 companies that produce ethylbenzene use this process.

(b) Ethylbenzene: mixed xylene extraction. Mixed xylene extraction is a refinery recovery process requiring feedstocks that yield xylenes with high EB content. It is economically competitive with benzene alkylation only when large quantities of fuel are available at low cost. Capacities based on xylenes are small compared to capacities based on benzene alkylation. Firms that distill EB from mixed xylenes and do not produce styrene are not included in this analysis.

Between 1965 and 1975, the percentage of total EB production based on xylenes declined from 11.4 percent to 2.6 percent. After increasing in response to demand pressure in the late 1960s, the absolute quantity produced from xylenes also declined.

TABLE 7-1. U.S. ETHYLBENZENE/STYRENE CAPACITY BY PRODUCER[1]

Company	Ethylbenzene		Styrene	
	Capacity (10^3 Mg/yr)	Cumulative % of total	Capacity (10^3 Mg/yr)	Cumulative % of total
Dow Chemical	847	17.9	861	21.0
Monsanto	794	34.6	680	37.7
Cos-Mar, Inc.	689	49.1	590	52.1
Oxirane	545	60.6	454	63.2
American Hoechst	526	71.7	450	74.2
Amoco	447	81.1	380	83.5
Gulf	313	87.7	272	90.1
Atlantic Richfield Co.	227	92.5	200	95.0
El Paso Products	125	95.2	115	97.8
Commonwealth Oil[a]	73	96.7	--	--
United States Steel	61	98.0	54	99.1
Sun Oil Co., Inc.	61	99.3	36	100.0
Charter Co.[a]	18	99.7	--	--
Tenneco[a]	16	100.0	--	--
TOTAL	4,742	100.0	4,092	100.0

[a] These companies distill ethylbenzene from mixed xylene streams for merchant sale. They do not produce styrene and will not be regulated under the EB/S standard. EPA plans to regulate benzene emissions from these operations with a petroleum refinery standard.

Although overall production in the EB/S industry is strongly sensitive to fluctuations in aggregate demand, the choice of production process is determined predominantly by supply considerations. As in the recent past, future production from xylenes may be limited by increasing production costs and limited availability of feedstocks. In the past, large amounts of cheap natural gas have been available to most producers. This will not continue to be true. Feedstocks that provide xylenes high in EB content may not always be available in the future. This combination of circumstances renders mixed xylene extraction relatively unattractive on economic grounds and is not expected to provide significant quantities of EB in the future.

(c) Styrene: ethylbenzene dehydrogenation. Over 88 percent of U.S. styrene capacity is based on catalytic dehydrogenation of EB. This process has been improved over time and production efficiencies vary with the age of the producing unit.[4] Prior to 1977, all U.S. styrene capacity was based on catalytic dehydrogenation. It is expected to continue to be the predominant process in the near future. Only one alternate process, propylene oxide coproduct, has had commercial application. Although it is competitive with dehydrogenation, it is not expected to replace dehydrogenation because it is a coproduct process.

(d) Styrene: propylene oxide coproduct. EB can be oxidized to its hyperoxide and reacted with propylene to produce propylene oxide and methyl phenyl carbinol, which is dehydrated to styrene. Although this process has been used in other parts of the world, only Oxirane Corp. uses it in the U.S. (the technology was developed by Halcon International, a joint owner of Oxirane).[5]

The economic efficiency of direct oxidation is determined by the markets for both styrene and propylene oxide. Although growth prospects for propylene oxide are good, some excess capacity is expected to persist in the near term.[6] Moreover, the market for propylene oxide is highly concentrated, with only five producers. Oxirane already was marketing propylene oxide from a different production facility when it constructed its coproduct plant. Other producers are reticent to adopt a process whose economic viability depends upon the firm entering a new, highly concentrated market. Similarly, propylene oxide producers currently are not interested in entering the styrene market, which also suffers from excess capacity. Consequently, major inroads by this process are not expected in the near term. However, it is one of the most efficient ways to produce propylene oxide[7] and provides styrene at competitive costs, assuming the producer has an outlet for propylene oxide. Consequently, it can coexist with dehydrogenation.

7.1.2.2 Resource Use

Estimates of base employment and energy use in the EB/S industry are necessary to assess the potential impact of controls on such resource use. A rough estimate of direct employment in the EB/S industry is 650 to 950 workers.[8] It is difficult to be more specific because of variations between plants and because companies sometimes are reluctant to provide this information. Energy use in the EB/S industry is estimated to be 25 megajoules per kilogram (MJ/kg) of production. This corresponds to approximately 78 million gigajoules (GJ) in 1978. In that year, EB/S production accounted for 47 percent of all benzene consumed in the United States, or 2.67 million megagrams (Mg).[9] Benzene consumption is of interest because benzene availability has been a problem for the industry in the recent past and could be again.

7.1.2.3 Product Use

Styrene is used in the manufacture of plastics and resin materials. These materials are high molecular weight polymers that can be shaped or otherwise processed through the application of heat and/or pressure. Plastics are solid forms that are molded, cast, or extruded; resins are solutions, pastes, or emulsions that can be used as coatings. There are two basic types of plastics and resin materials: thermosetting materials, which can be softened or shaped only once by heat or solvents, and thermoplastic materials, which can be repeatedly softened and shaped by heat.[10] Styrene materials are generally thermoplastics.

The predominant thermoplastic material produced from styrene is polystyrene. As shown in Table 7-2, 1976 production of polystyrene accounted for 62 percent of total styrene consumption. Polystyrene is a medium strength, rigid, easily dyeable material of relatively low cost. It is used in packaging, food containers, insulation, furniture parts, and "styrofoam." Polystyrene demand grew by more than 13 percent per year in the 1960's because of its low cost vis-à-vis competing materials. As its price increased during the 1970's, it became less competitive. As a result, some

TABLE 7-2. PRODUCT CONSUMPTION -- PERCENT BY INTERMEDIATE USE[5]

Intermediate Uses (1976)	Percent of Domestic Production	Percent of Domestic Consumption
Ethylbenzene uses:		
Styrene	98[a]	99
Other	2[a]	1
	100	100
Styrene uses:		
Polystyrene	54	62
Other styrene copolymers	17	20
Styrene-butadiene elastomers (SBR)	9	11
Unsaturated polyester resins	6	7
Miscellaneous	1	1
Net exports	13	--
TOTAL	100	101

[a] Estimates for 1975.

substitution of polypropylene, wood, and paper products for polystyrene has taken place. Substitution may continue, but it is not expected to prevent all growth in the polystyrene market. Projected growth through 1985 of six percent per year is lower than it has been in the past because of product competition and mature markets for the final goods produced. But growth will continue because of the low capital cost requirements in processing polystyrene and the high costs of switching input materials. Also, in some situations polystyrene is so much more suitable technically than other materials that substitution is unlikely in the near term.

Other styrene copolymers include acrylonitrile-butadiene-styrene (ABS) resins, styrene-acrylonitrile (SAN) resins, and styrene-butadiene copolymer latexes. ABS resins are used in pipe and in automotive and appliance applications. SAN resins are used in houseware and automobile transparent panels and windows. Copolymer latexes are used in paper coatings and carpet backing. These uses accounted for 20 percent of U.S. styrene consumption in 1976 (Table 7-2). Like polystyrene, these products face mature markets but still some growth is expected.

In 1976, styrene-butadiene elastomers (SBR) accounted for 11 percent of domestic consumption of styrene, its primary use being the manufacture of synthetic rubber. Final goods produced include tires, hoses, belting, and adhesives. This market currently is depressed because of the weak tire market.[4] Increased tire life has created a substantial inventory buildup which will persist for some time. Little, if any, growth is expected in this market nor is substitution of other materials.

Unsaturated polyester resins are used in transportation-related and construction materials. These applications accounted for seven percent of domestic consumption in 1976. This market should continue to grow.

Substitutes for styrene materials include more basic products like wood, glass, and paper. As noted, there has been some substitution of these goods for styrene products due to styrene price increases. However, this type of substitution is limited because, in many cases, plastic materials originally replaced these products as a result of their technical superiority. A return to basic products will be avoided unless the price of plastics becomes very high indeed.

Styrene plastics may be supplanted by other plastics to some degree if prices continue to increase. As noted, polypropylene has replaced polystyrene in some applications. There also may be cost advantages to substituting polyvinyl chloride or polyethylene for some styrene-based plastics.[11] Thus far, the fear that other polymers, especially polypropylene, would substantially replace styrene materials has proved unjustified,[12] indicating that either the technical difficulties or the costs of substitution are greater than initially indicated.

Table 7-3 presents final uses for styrene materials ranked according to percentage of domestic styrene production and consumption. Packaging is the predominant use and this is not expected to change in the near future. Construction-related uses are second in importance, followed by electrical goods, household goods, and transportation-related applications.

7.1.3 Production Trends

From 1961 to 1976, styrene production increased by an average of over eight percent per year while the Gross National Product (GNP) increased by an average of less than four percent per year. However, this average is not representative of activity during the entire period. From 1960 to 1972, annual growth averaged ten to 11 percent.

TABLE 7-3. STYRENE CONSUMPTION -- PERCENT BY FINAL USE[13]

Final Uses (1974)	Percent of Domestic Production	Percent of Domestic Consumption
Packaging	22	23
Construction-related	16	17
Electrical goods (incl. appliances)	12	13
Household goods (excl. appliances)	12	12
Transportation-related	10	10
Recreational goods (incl. toys, sporting gds.)	8	9
Disposable serviceware	4	5
Miscellaneous	11	11
Exports	5	--
TOTAL	100	100

As shown in Table 7-4, production increased most dramatically in 1969 and again in 1972. However, year-to-year variations during this period resulted predominantly from the normal vicissitudes of business. Beginning in 1973 this was not the case. Production remained approximately constant from 1973 to 1974. Demand was not static in this period but supply was. The Mideast oil crisis affected the EB/S industry as it did most petroleum-related production. EB/S production was constrained by overall benzene shortages. Note that while production remained constant, capacity increased by over nine percent. Capacity utilization declined from 91 percent to 83 percent.

In 1975, production declined from 2,701,000 Mg to 2,119,000 Mg, or by over 21 percent. Capacity increased by over nine percent and utilization

TABLE 7-4. HISTORICAL DOMESTIC STYRENE CAPACITY AND PRODUCTION[1,14,15]

Year	Capacity (10^3 Mg)	Production (10^3 Mg)
1960	844	791
1961	998	799
1962	1,068	881
1963	1,109	977
1964	1,268	1,166
1965	1,417	1,299
1966	1,460	1,447
1967	1,574	1,487
1968	1,846	1,677
1969	2,086	2,108
1970	2,086	1,966
1971	2,696	2,123
1972	2,812	2,694
1973	2,984	2,710
1974	3,256	2,701
1975	3,392	2,119
1976	3,712	2,858
1977	4,200	3,114
1978	4,092	3,119[a]

[a] Provisional Estimate, U.S. International Trade Commission.

decreased to 62 percent. Just as benzene shortages eased, demand decreased substantially as a result of general worldwide recession. In 1976, production increased by almost 35 percent to levels above those characteristic of the early 1970's. However, capacity again increased by over nine percent. Capacity utilization in 1976 was approximately 77 percent. Production increased by nine percent in 1977 and remained approximately static in 1978. Finally, capacity increased by 13 percent in 1977 and decreased by over three percent in 1978.

The phenomenon of increasing capacity in the presence of a production slack during this period requires some explanation. The 1960 to 1978 period was characterized by increasingly larger individual production facilities. The replacement of small capacity facilities with large capacity facilities was dictated by the economics of production over the long term. In particular, the potential for economies of scale was recognized. This process exacerbated excess capacity problems at times.

7.1.4 Prices

Table 7-5 presents a price history for styrene which includes published list prices as well as unit sales values. Unit sales values represent average prices actually paid and are generally indicative of contract prices for styrene. Since large amounts of styrene are traded in this manner, unit sales values frequently are more useful than list prices.

Both list prices and unit sales values decreased from 1960 to 1965. In fact, list price and market sales values had been declining since 1952 when the list price was \$463/Mg and the unit sales value was \$353/Mg. Increased technical efficiency and scale of operation are the most probable explanations of this decline. From 1965 to 1972, list price fluctuated at about

TABLE 7-5. STYRENE PRICE HISTORY[15,16,17]

Year	Cents per Kilogram		Dollars per Metric Ton (Mg)	
	List Price	Unit Sales Value	List Price	Unit Sales Value
1960	27.6	25.1	275.58	251.32
1961	24.3	23.5	242.51	235.45
1962	23.2	22.1	231.48	221.12
1963	23.2	20.4	231.48	204.15
1964	20.9	17.9	209.44	178.57
1965	17.6	16.8	176.37	168.21
1966	19.8	17.7	198.41	177.03
1967	18.7	17.0	187.39	169.97
1968	16.5	14.8	165.34	147.49
1969	18.1	14.0	180.78	139.99
1970	17.6	14.3	176.37	142.64
1971	17.6	13.3	176.37	132.94
1972	17.6	12.6	176.37	125.88
1973	15.9	15.5	158.73	154.54
1974	44.1	38.0	440.92	380.07
1975	48.5	41.3	485.01	412.48
1976	46.3	43.4	462.97	433.87
1977	46.3	41.0	462.97	409.84
1978	46.3	--	462.97	--

the 1965 level but unit sales value continued to decline. In 1972, list price was almost 40 percent above unit sales value. Then, in 1973, list price declined and unit sales value rose, bringing the two values back into line with each other.

Late in 1973, styrene prices began to be forced up by benzene shortages. In 1974, list price almost tripled and unit sales value more than doubled. This increase was the result of more than just benzene shortages. Other factors influencing price included: (1) the removal of 1973 price controls;

(2) the fourfold increase in crude oil prices, which increased both raw material and energy costs; and (3) an increase both in investment values, reflecting higher capital costs, and in returns on investment, generating higher profitability levels.[18] List price rose again in 1975 and then declined slightly in 1976 to $462.97/Mg, where it stayed for several years. In early 1979, list price again began to move upward. In May 1979, announced prices reached $683.43/Mg. These increases reflect rapidly escalating benzene prices and strong European demand for many petrochemicals. It is not yet clear where the price will stabilize.

Both list prices and published unit sales values must be interpreted with some caution. An announced list price may or may not have associated with it a discount, sometimes called a "temporary allowance."[19] Even though list price may remain unchanged for a substantial period, it is not unlikely that discounts offered vary over that period. Similarly, producing company policy with regard to the payment of transportation costs can introduce a differential between either contract or spot price and the effective price paid. Producers sometimes absorb transportation costs, but not always. Absorption of such costs will vary with customer, delivery location, and market conditions.[20] Consequently, both list price and unit sales value should be treated as average values only.

7.1.5 International Trade

In 1976, approximately 40 percent of world styrene capacity was located in the United States and Puerto Rico. At that time, Western Europe had 34 percent of world capacity and Asia had 20 percent. These proportions should change some in the near future because European styrene capacity is increasing vis-a-vis U.S. capacity. These increases are expected to alter the current U.S. export position during the 1980's.

Traditionally, the U.S. has been a net exporter of styrene (see Table 7-6). In many years, exports have represented a substantial portion (ten to 15 percent) of U.S. production. In 1975, 67 percent of exports went to Western Europe and 27 percent went to Latin America. At maximum, imports have represented one to two percent of total consumption. Imports generally have come from Canada.

TABLE 7-6. STYRENE EXPORTS AND IMPORTS (10^3 Mg)[21]

Year	Exports	Imports	Net Exports
1960	71.7	N.A.[a]	--
1961	62.6	N.A.	--
1962	55.7	N.A.	--
1963	54.6	N.A.	--
1964	155.0	N.A.	--
1965	166.2	N.A.	--
1966	163.1	N.A.	--
1967	197.8	N.A.	--
1968	243.8	N.A.	--
1969	377.1	N.A.	--
1970	257.4	4.6	252.8
1971	167.4	0.2	167.2
1972	299.8	11.2	288.6
1973	260.6	14.0	246.6
1974	282.3	27.6	254.7
1975	260.4	3.0	257.4
1976	431.6[b]	11.2[b]	420.4
1977	445.9[c]	3.0[d]	442.9
1978	357.2[c]	14.0[d]	343.2

[a] Accurate estimates of imports in this period are difficult to obtain because of the manner in which data are grouped in Department of Commerce publications.

[b] Personal communication. Bureau of the Census, Foreign Trade Division, Chemicals Section.

[c] Chemical Marketing Reporter. March 26, 1979. p. 11.

[d] Chemical Marketing Reporter. March 19, 1979. p. 11.

Exports are expected to decline as capacity increases in Western Europe. This decline may be proceeding more slowly than anticipated because of problems with naphtha availability in Europe in 1979. Small European capacities, together with lower freight rates to Europe from the U.S. than from Japan, have given U.S. producers an advantage in the past. However, this and the other U.S. advantage, lower raw material costs, are disappearing. In addition, the styrene industry has been increasingly characterized by U.S. companies with European affiliates and European companies with U.S. affiliates. As a result, experts anticipate smaller future styrene price differentials between the U.S. and Europe.[22] Table 7-7 presents unit sales values for both domestic and export sales. Note that differences between

TABLE 7-7. STYRENE UNIT SALES VALUES FOR DOMESTIC AND EXPORT MARKETS (Dollars per Metric Ton or Mg)[23,24]

Year	Domestic Unit Sales Value	Export Unit Sales Value
1965	168.21	180.78
1966	177.03	154.30
1967	169.97	145.50
1968	147.49	138.89
1969	139.99	138.89
1970	142.64	141.09
1971	132.94	123.46
1972	125.88	127.87
1973	154.54	299.83
1974	380.07	529.10
1975	412.48	392.42
1976	433.87	--
1977	409.84	399.76

these values vary considerably from year to year in both magnitude and direction.

7.1.6 Market Structure

7.1.6.1 Firm Characteristics

Table 7-8 shows U.S. styrene producers, their plant locations and capacities, and some indication of the degree of vertical integration in the EB/S industry. Note that all styrene manufacturers produce ethylbenzene also. In some integrated operations EB is not separated as such; however, in most cases, EB and styrene are produced in the same basic location. When they are not, styrene production coincides locationally with the production of styrene derivatives, as opposed to feedstocks (EB). Eight of the 11 EB/S firms also produce styrene derivatives. Of those three that do not, two (El Paso Products and Sun Oil Co., Inc.) produce relatively small amounts of styrene.

Something akin to horizontal integration is also characteristic of the EB/S industry in the 1970's. Two producers, Cos-Mar and Oxirane, are separate operating companies, each of which is owned jointly by other companies. Cos-Mar is owned jointly by Borg-Warner (30.8 percent) and American Petrofina (69.2 percent). Each of these companies previously has owned and operated a styrene plant of its own. Oxirane is owned by Atlantic Richfield (50 percent) and Halcon International (50 percent). Atlantic Richfield owns other existing styrene capacity.

These operating companies were not "taken over" by existing companies, as would be typical of horizontal integration. Rather, they were created by the existing companies to meet their needs for EB/S capacity in the most efficient manner. A jointly owned operating capacity allows each owner to achieve the economies of large-scale production without building a much larger plant

TABLE 7-8. U.S STYRENE PRODUCERS -- LOCATION, CAPACITY. AND INTEGRATION[1,25]

Company	Plant Location	Capacity (10^3 Mg)	Company Produces EB?	Company Produces Styrene Derivatives?
American Hoechst Corp.	Baton Rouge, LA	450	yes	yes
Amoco	Texas City, TX	380	yes	yes
Atlantic Richfield Company (ARCO)	Port Arthur, TX	227 (EB)	yes	no
	Kobuta, PA	200 (S)	no	yes
Cos-Mar, Inc.	Carville, LA	590	yes	yes[a]
Dow Chemical USA	Bay City/Midland, MI	181	no	yes
	Freeport, TX	680	yes	yes
El Paso Products	Odessa, TX	115	yes	no
Gulf Oil Corp.	Donaldsonville, LA	272	yes	no
Monsanto Co.	Texas City, TX	680	yes	yes
Oxirane Corp.	Channelview, TX	545	yes	yes[a]
Sun Oil Co., Inc.	Corpus Christi, TX	36	yes	no
United States Steel	Houston, TX	54	yes	yes

[a] Cos-Mar is a joint venture involving Borg-Warner Corp. and American Petrofina, Inc. Each produces a styrene derivative. Oxirane is a joint venture of Halcon International and Atlantic Richfield which produces styrene derivatives.

than it needs or wants. Oxirane, in particular, functions as a reliable source of additional styrene for several existing companies. Its existing capacity has been sold out "long term" to several producers: Atlantic Richfield (an owner), American Hoechst, Borg-Warner, and Gulf.[26]

The economies of large-scale operation are not process-related. They do not involve lower costs in terms of raw material, energy, or labor usage.* These economies do involve spreading overhead and possibly achieving lower capital requirements per unit of capacity. This analysis is supported by an examination of styrene plants over time. In 1960, total styrene capacity was 844,000 Mg. There were nine plants with an average size of 94,000 Mg, the largest of which produced 236,000 Mg. By 1965, all of those plants had expanded and several had been added. By 1970, more plant expansion had occurred and Cos-Mar came on stream. In 1970, average plant size was 152,000 Mg and the largest had a capacity of 363,000 Mg. By 1978, average size was 337,000 Mg and the largest had a capacity of 680,000 Mg. The average size increased because new large plants came on stream, some existing plants were expanded, and some older, small plants were phased out.

It is important to note that not all large plants represent single large production units. Some, like Oxirane, represent a single production train. Others, like the Dow plant in Texas, represent multiple units. Moreover, multiple units are not necessarily of the same age, so that a given plant may not have "an" age, but rather, multiple ages.

Table 7-9 presents some further information on selected owners of styrene capacity. Rough estimates of styrene sales by company were made to

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*Existing smaller plants are less efficient in these terms, but this is not because they are smaller so much as because they are older.[27]

TABLE 7-9. FINANCIAL CHARACTERISTICS OF SELECTED STYRENE PRODUCERS[28]

Company	Year	Debt-Equity Ratio	After-Tax Rate of Return on Equity[a] (%)	Styrene Sales as a % of Revenues[b]
American Petrofina (joint owner, Cos-Mar)	1977	0.638	10.3	11.4
Amoco	1977	0.910	15.0	0.8
Atlantic Richfield (ARCO + joint owner, Oxirane)	1977	1.245	14.2	1.3
Borg-Warner (joint owner, COS-MAR)	1977	0.664	11.9	5.3
Dow Chemical	1977	1.462	17.8	4.1
Gulf Oil	1977	0.939	10.2	0.4
Monsanto	1977	0.812	11.5	4.5
Sun Oil Co., Inc.	1977	0.211	13.1	2.6

[a] After-tax rates of return were calculated using the individual companies' own assessments of after-tax income. The size and diversification of the companies and the types of markets in which they operate make their tax structures very complex.

[b] Styrene sales were estimated by applying a capacity utilization rate of 74 percent (1977 average) to each company's capacity to estimate production and multiplying this by the 1977 unit sales value ($409.84/Mg).

determine their degree of importance in overall company revenues. Styrene sales represent between 0.4 percent (Gulf) and 11.4 percent (American-Petrofina) of total company revenues. All of the companies examined are highly diversified. In fact, the only styrene producers that are not highly diversified are the operating companies, Cos-Mar and Oxirane, and the owners of those companies are themselves highly diversified.

After-tax rates of return on equity vary across the selected companies. The lowest value is 10.2 percent for Gulf Oil and the highest value is

17.8 percent for Dow Chemical. Debt-equity ratios also vary, with the lowest value being 0.211 for Sun Oil Co., Inc. and the highest being 1.462 for Dow Chemical. Even the highest ratio is sufficiently low so that debt financing should not present a problem for any of these companies.

7.1.6.2 Market Concentration

Table 7-10 presents market concentration ratios for the styrene industry for 1960, 1965, 1970, 1975, and 1978. Dow Chemical is the largest single producer in each of those years. However, its share of the U.S. market has declined from 33.5 percent to 21.3 percent. It is interesting to note that in 1976, Dow's worldwide holdings represented 17 percent of total world styrene capacity.[30] In 1960, the top two and top four firms represented 61.5 and 81.3 percent, respectively, of total U.S. capacity. Comparable figures for 1978 are 38.1 percent and 63.9 percent. Concentration ratios for SIC 2865 (Cyclic Crudes and Intermediates), of which styrene is a part, show the top four and top eight companies accounting for 34 percent and 52 percent of shipments, respectively. Thus, styrene manufacture is a

TABLE 7-10. CONCENTRATION IN THE STYRENE INDUSTRY[1,29]
Percent of Total Production Capacity Accounted for by
Largest 1, 2, 4, and 8 Styrene Manufacturers

Year	Largest 1	Largest 2	Largest 4	Largest 8	Total Number of Manufacturers
1960	33.5	61.5	81.3	100.0	8
1965	26.2	46.9	68.8	95.3	11
1970	19.2	35.1	62.8	90.4	12
1975	24.7	44.8	69.3	95.7	11
1978	21.3	38.1	63.9	96.1	11

highly concentrated segment of an overall industry group that is itself rather concentrated.

Concentration alone is not sufficient to guarantee market power. In the case of the EB/S industry, several factors weaken the potential power created by concentration. The fact that the product generated is an intermediate good, which is not differentiated by producer, increases the likelihood of competition.* Currently there is excess capacity in the EB/S industry, which also makes it difficult for producers to manipulate product price. Of course, as capacity is approached, this constraint is weakened. The existence of an international market also weakens domestic market power. The U.S. traditionally has been an exporter and not an importer of styrene, but existing trends indicate that this will not continue. Price differentials between the U.S. and Europe are expected to decrease, increasing the competitive potential of foreign producers. Finally, the existence of some substitute materials in the form of other plastics increases the likelihood of competition.

Examination of the pricing process in the EB/S industry supports the theory that market power currently is not as great as concentration ratios might indicate. There does not appear to be any established price leader in the industry. Price increases sometimes have been announced by individual firms and then retracted when other firms did not increase prices also. Concern about whether price increases will "hold" appears to be not uncommon in the industry. Thus, while there appears to be some market power in the industry, it is not unrestrained.

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*Chemical products are more likely to be differentiated by buyer than by producer. That is, the producer sometimes tailors the product to buyer specifications.

7.1.7 Supply and Demand

7.1.7.1 Supply

No attempt was made to estimate econometrically a supply function for the styrene industry. Nevertheless, it is clear that the quantity of styrene supplied is affected materially by the price of styrene and the prices of the inputs used to produce styrene. Also, the quantity supplied reflects any input availability problems that are not captured fully by the prices of those inputs. For example, in 1974, benzene shortages substantially constrained the production of styrene.

Important input prices which affect styrene supply include prices of feedstocks, labor, machinery and equipment, and fuels. Feedstocks and fuels have had particular impact in the recent past. Primary feedstocks in the EB/S industry are benzene and ethylene. The market for ethylene has been comparatively stable. This is not expected to change. However, the market for benzene presents more of a problem. Benzene is a petrochemical and its market reflects any upheaval in the petroleum market. Benzene prices have increased considerably in the recent past. Recent price increases for styrene substantially reflect these increases in feedstock costs.

Energy costs also have increased substantially. Frequently, fuels are purchased on relatively long-term contracts. When contracts expire and are renegotiated, fuel prices can increase considerably. In 1977, it was estimated that plants using "old gas," i.e., gas contracted for at "old" prices, had fuel costs of approximately 1.1¢ per kilogram of styrene. It was anticipated that at contract renegotiation those prices could increase to between 4.4¢ and 5.5¢ per kilogram of styrene.[26]

Styrene supply also could be influenced by the market for propylene oxide as a result of the coproduct process. The profitability of the coproduct process depends upon the markets for both styrene and propylene oxide. Should the demand for propylene oxide alter substantially, it could induce changes in the quantity of styrene supplied.

7.1.7.2 Demand

A derived demand function for styrene was estimated using time series data for 1958 to 1973. Although data for 1974 to 1977 were available, they were excluded because observations for those years were not consistent with previous data. Input availability problems in 1974 could have been handled through the use of dummy variables (an econometric technique) had there been no further complications. But upheaval in the petroleum market and consequent price increases created further difficulties. For example, the price index used to adjust styrene prices probably is not appropriate for the period after 1973 and cannot be used to generate true relative price changes for the plastics industry. Please note that any application of estimates generated for the period 1958 to 1973 to later periods requires the assumption that there has been no major structural change in the demand relationship. A shift of some kind certainly occurred after 1973, but a simple upward shift need not invalidate econometric estimates.

The equation estimated through ordinary least squares is:

$$\ln QSTY = \underset{(1.67)}{2.74} - \underset{(0.24)}{0.49^*} \ln RSP + \underset{(0.34)}{1.36^*} \ln RINC; \; R^2 = 0.986 \qquad (1)$$

where

QSTY = quantity of styrene produced

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*These coefficients are significant at the 90 percent confidence level.

RSP = relative price of styrene

= (styrene price × 100)/(styrene price, 1958 × PI)

RINC = real income = (GNP/PI) × 100

GNP = Gross National Product

ln = natural logarithm

PI = price index.

Numbers in parentheses present the standard errors of the coefficient estimates. This equation represents a long-run demand function. Note that the relative price of styrene (RSP) and real income (RINC) both generate significant coefficients with the expected signs, e.g., the quantity of styrene demanded varies inversely with the price of styrene and directly with real income.

Also note that the coefficient of real income is much larger than the coefficient of styrene price. This supports the statement that styrene demand is tied closely to the performance of the overall economy. As the equation is estimated in natural log form, the coefficient of the styrene price variable is the negative of the price elasticity of demand for styrene.

7.1.8 Baseline Projection

7.1.8.1 Baseline Regulatory Environment

The industry is assumed to be in compliance with existing regulations prior to enforcement of standards considered here. Accordingly, estimated costs of control (Section 7.2) are incremental costs associated with increased pollution control.

7.1.8.2 Baseline Growth Rates

The demand for styrene in the future will be tied closely to the performance of the overall economy. Significant market penetration in existing styrene uses indicates that future demand for styrene will depend upon final demands for the goods produced. While these goods satisfy a variety of consumer needs, the demands for these goods tend to be sensitive to overall income trends.

Several other factors have the potential to influence styrene demand, but are not expected to be of major importance. New use development is always a possibility and could cause an increase in the demand for styrene. But significant new use creation is not foreseen in the near future. Competition among various polymers could alter styrene demands. If styrene were to replace other polymers, the demand for styrene would increase. During the 1960's, considerable demand growth occurred in this manner, but this is not expected to continue. If styrene were replaced by other polymers, demand for styrene would be affected negatively. Some such replacement has been feared for several years, but has not been forthcoming. Some experts now feel that competition among polymers will have only small net effects on the various markets involved.[31] They reason that new-use development is more profitable than the capture of markets from other polymers. Thus, producers of competing materials may not be actively seeking to capture styrene markets.

Several sources estimate growth rates for styrene consumption based on projected demands for derivative products. SRI International predicts annual growth rates of four to six percent for styrene demand through 1980.[32] One industry source predicts an annual growth rate of five percent through 1985.[33] The National Petroleum Refiners Association predicts a growth rate of five percent per year through 1987.[34] Thus, five percent is taken to be a best estimate for the period 1979 to 1985. Assuming a five percent annual growth rate, styrene demand in 1985 would be 4,389,000 Mg.

7.1.8.3 Baseline Investment Projections

Existing capacity is 344,000 Mg short of projected demand for 1985. Furthermore, a portion of existing capacity certainly will be retired by 1985 and require replacement. Without more specific information on the age structure of existing plants, it is difficult to estimate replacement needs, but it is reasonably certain that most of the smaller units still in existence will be retired over this period.

One industry expert estimates that approximately 30 percent of 1976 capacity was made up of smaller, older, less efficient units that could be expected to shut down by 1982.[26] Feedstock, fuel, and labor utilization are all relatively poor for these units. In fact, several such plants have closed already, representing approximately five percent of 1976 capacity. If the prediction that 30 percent will close is correct, closures amounting to 928,000 Mg are still to come. If such closures are forthcoming, total new capacity of 1,200,000 to 1,300,000 Mg will be required by 1985. Given typical sizes of units constructed in the recent past, three to four new units will be needed to meet this demand, assuming full or nearly full utilization of all units. Note that new units do not necessarily mean new producers or new plant locations, since additions, expansions, or replacements at existing sites are common in the EB/S industry.

7.2 COST ANALYSIS OF ALTERNATIVE EMISSION CONTROL SYSTEMS

7.2.1 Introduction

This section presents capital and annualized control costs for three of the four benzene emission regulatory options under consideration. The costs are presented on a plant-by-plant basis for each of the facilities producing EB/S identified in Chapter 3. No data are presented for those facilities producing ethylbenzene from mixed xylenes.

The three regulatory options for which cost data are presented are:

- Regulatory Option A (85 percent control) -- achievable by routing emission streams to either a scrubber or condenser system.
- Regulatory Option B (94 percent control) -- achievable by coupling a flare system to the scrubber/condenser system of Regulatory Option A.
- Regulatory Option C (99 percent control) -- achievable by routing emission streams to an existing boiler.*

Under each option the continuous release of the hydrogen separation vent is routed to a process heater (99 percent control).

7.2.2 Equipment Used

7.2.2.1 85 Percent Control with a Scrubber and Condensers -- Regulatory Option A

This analysis assumed that 85 percent control can be achieved using a scrubber and condenser system. The scrubber (absorption tower) operates with lean** polyethylbenzene (PEB) oil which is recycled back to the process. The scrubber is designed to control continuous venting from the alkylation reactor and all vacuum columns in the EB/S facility with the exception of the benzene/toluene column(s). The condenser system for each facility consists of two condensers, one of which controls the benzene/toluene hotwell vent(s) and the other which controls the combined vent emissions from all of the columns operating at atmospheric pressure and above. The vent streams from the condenser and scrubber system are then released to the atmosphere.

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*Boiler includes process heaters, superheaters, and other similar units.

**Lean indicates an absence of benzene.

7.2.2.2 94 Percent Control with a Flare -- Regulatory Option B

This analysis assumed that 94 percent control can be achieved with a flare system when it is used in conjunction with a scrubber and condenser system. The 94 percent control is based on an 85 percent reduction of benzene with a scrubber and condenser system identical to the one mentioned above in addition to a 60 percent reduction with a flare. The vent streams from the condenser and scrubber system are then manifolded into a flare header which is attached to a flare which has been sized to handle the continuous vent releases. Figure 7-1 presents a schematic of the option described here. Table 7-11 presents a list of equipment assumed necessary to achieve this level of control.

7.2.2.3 99 Percent Control with a Boiler -- Regulatory Option C

Under this regulatory option all of the vents are manifolded together and the combined vent stream then is routed to an existing boiler. In order to combust the vent stream, which is at a relatively low pressure when compared to normal fuel line pressures, the boiler either must be retrofitted with a burner which uses high pressure air to aspirate the vent stream into the burner, or the vent stream must be compressed to 30 psi or greater and introduced into the boiler fuel system where it can be combusted. In either case, compressors are necessary when vent streams are to be compressed up to 300 psig and introduced into the main fuel system. Figure 7-2 presents a schematic of the option described here. Table 7-11 presents a list of the equipment needed to achieve this level of control.

FIGURE 7–1
SCHEMATIC OF 94% REGULATORY OPTION

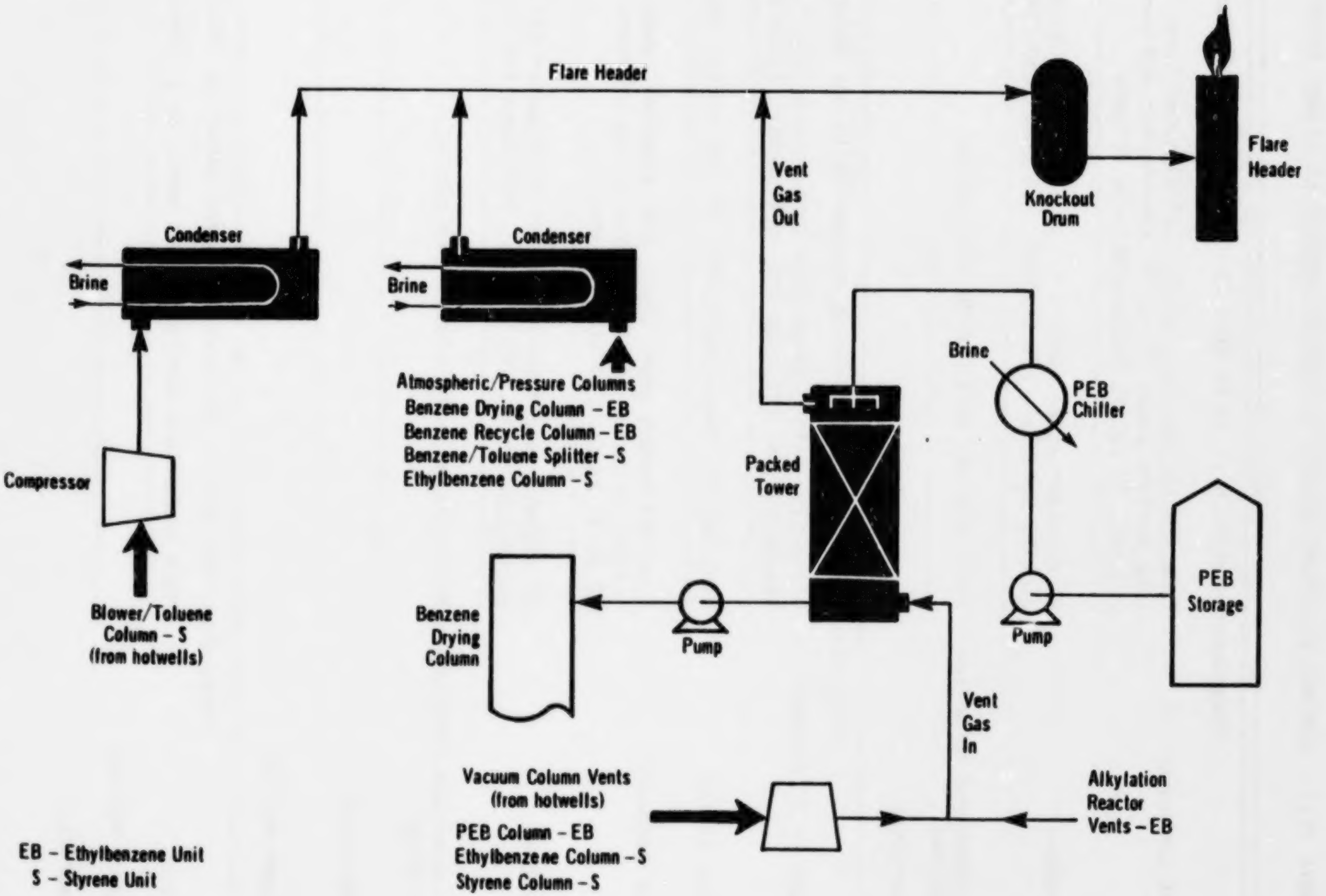
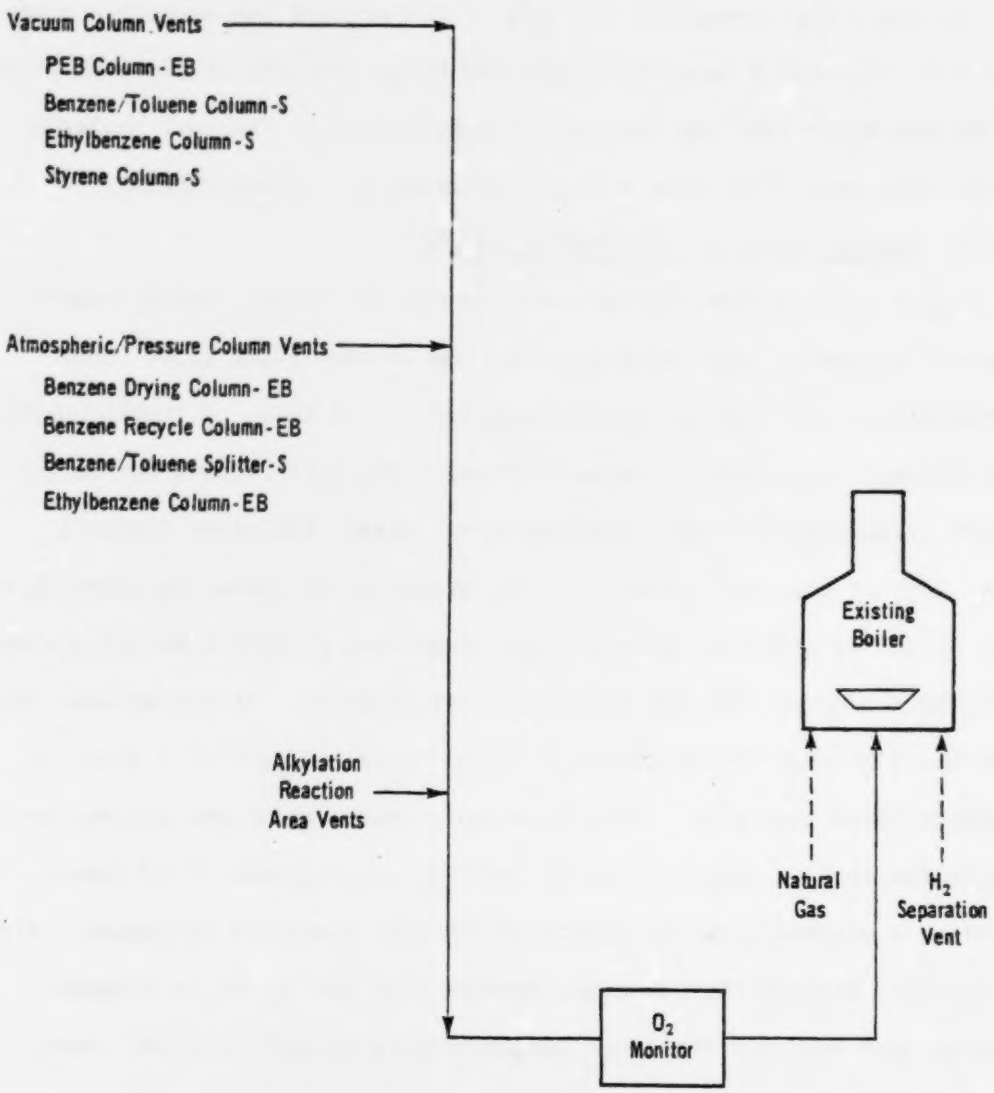

Flare Header
Knockout Drum
Flare Header
Vent Gas Out
Condenser
Brine
Condenser
Brine
Compressor
Blower/Toluene Column – S (from hotwells)
Atmospheric/Pressure Columns
Benzene Drying Column – EB
Benzene Recycle Column – EB
Benzene/Toluene Splitter – S
Ethylbenzene Column – S
Packed Tower
Brine
PEB Chiller
PEB Storage
Pump
Benzene Drying Column
Pump
Vent Gas In
Vacuum Column Vents (from hotwells)
PEB Column – EB
Ethylbenzene Column – S
Styrene Column – S
Alkylation Reactor Vents – EB
EB – Ethylbenzene Unit
S – Styrene Unit

TABLE 7-11. CONTROL EQUIPMENT NEEDED TO ACHIEVE BENZENE EMISSIONS REDUCTION

(Regulatory Option A -- 85 Percent Benzene Emissions Reduction)	
Vent condenser	Type AEM carbon steel shell 3/4" diameter tubes. Tube surface areas 68 sq. ft atmospheric and pressure columns, 32 sq. ft benzene/toluene columns
Scrubber	9" diameter steel shell 6 ft of 1" diameter Raschig ring packing material, PEB chiller, PEB pumps and controls
Scrubber and condenser piping	Brine piping, vent piping, PEB piping
Compressor	
(Regulatory Option B -- 94 Percent Benzene Emissions Reduction)	
Flare -- 3" diameter	Flare tip, pilot, steam injectors, stack, water seal, knockout drum, controls and instruments, flare base
Flare piping	Vent header, drain and sewer, air and water, natural gas
Vent condenser	Type AEM carbon steel shell 3/4" diameter tubes. Tube surface areas 68 sq ft atmospheric and pressure columns, 32 sq ft benzene/toluene columns
Scrubber	9" diameter steel shell 6 ft of 1" diameter Raschig ring packing material, PEB chiller, PEB pumps and controls
Scrubber and condenser piping	Brine piping, vent piping, PEB piping
Compressor	
Oxygen monitor	
(Regulatory Option C -- 99 Percent Benzene Emissions Reduction)	
Piping	Vent header and manifolding of vents to a common system
Oxygen monitor	
Compressor	

FIGURE 7-2

BURNER SYSTEM DIAGRAM


Vacuum Column Vents
PEB Column - EB
Benzene/Toluene Column - S
Ethylbenzene Column - S
Styrene Column - S
Atmospheric/Pressure Column Vents
Benzene Drying Column - EB
Benzene Recycle Column - EB
Benzene/Toluene Splitter - S
Ethylbenzene Column - EB
Alkylation Reaction Area Vents
Existing Boiler
Natural Gas
H_2 Separation Vent
O_2 Monitor

7.2.3 Equipment Costs

7.2.3.1 Introduction

The capital, operating, and maintenance costs for all of the control equipment considered are based on the stream characteristics shown in Table 7-12.

The quantities presented in Table 7-12 represent the emissions from a model facility with a capacity of 300,000 Mg/yr (330,000 tons/yr) of styrene and 345,000 Mg/yr (380,000 tons/yr) of ethylbenzene. The cost analysis assumes that vent flows show a linear relation with plant capacity.

7.2.3.2 Capital Costs for Control Equipment

Figure 7-3 presents capital costs curves for flares, flare headers, burners,* scrubbers, and condensers for the various plant sizes under consideration. All capital costs presented are in terms of fourth quarter 1978 dollars. The costs presented include installation costs but do not include allowances for fees, contingencies, taxes, and other indirect costs. All of the cost curves with the exception of those representing the total installed costs of scrubbers and condensers exhibit a marked plateau below 150,000 Mg/yr (165,000 tons/yr) plant capacity. It was assumed that there would be very little change in total installed cost of a piece of equipment below this size. This is because installation and piping contribute the most to total installed cost for small pieces of equipment. In addition, a minimum size was specified for some pieces of equipment. Also, the analysis assumed that no pipes smaller than two inches in diameter would be used and that the total length of pipe needed would not change

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*Burners refer to the equipment needed to introduce the vent streams into the combustion device and include a compressor piping and aspirating burner if necessary.

TABLE 7-12. ASSUMED VENT STREAM CHARACTERISTICS[a] 300,000 Mg/yr STYRENE CAPACITY MODEL UNCONTROLLED PLANT

	Alkyl Reaction Area Vents	Atm/Pressure Column Vents	Vacuum Column Vents		Hydrogen Separation Vent
			B/T[b]	Other	
Total					
kg/hr	112	100	25	11.2	6,700
liters/hr at STP	100,000	60,000	15,000	10,000	14×10^6
Weight %					
Benzene	10	45	45	15	6
Other Aromatics	-	5	5	5	30
C_1	32	12	12	30	
C_2/C_5	10	20	20	5	2
Inerts[c]	48	18	18	45	62
kg/hr					
Benzene	11.2	45	11.2	1.7	
Total Combustible VOC	58.0	82	20.0	7.0	

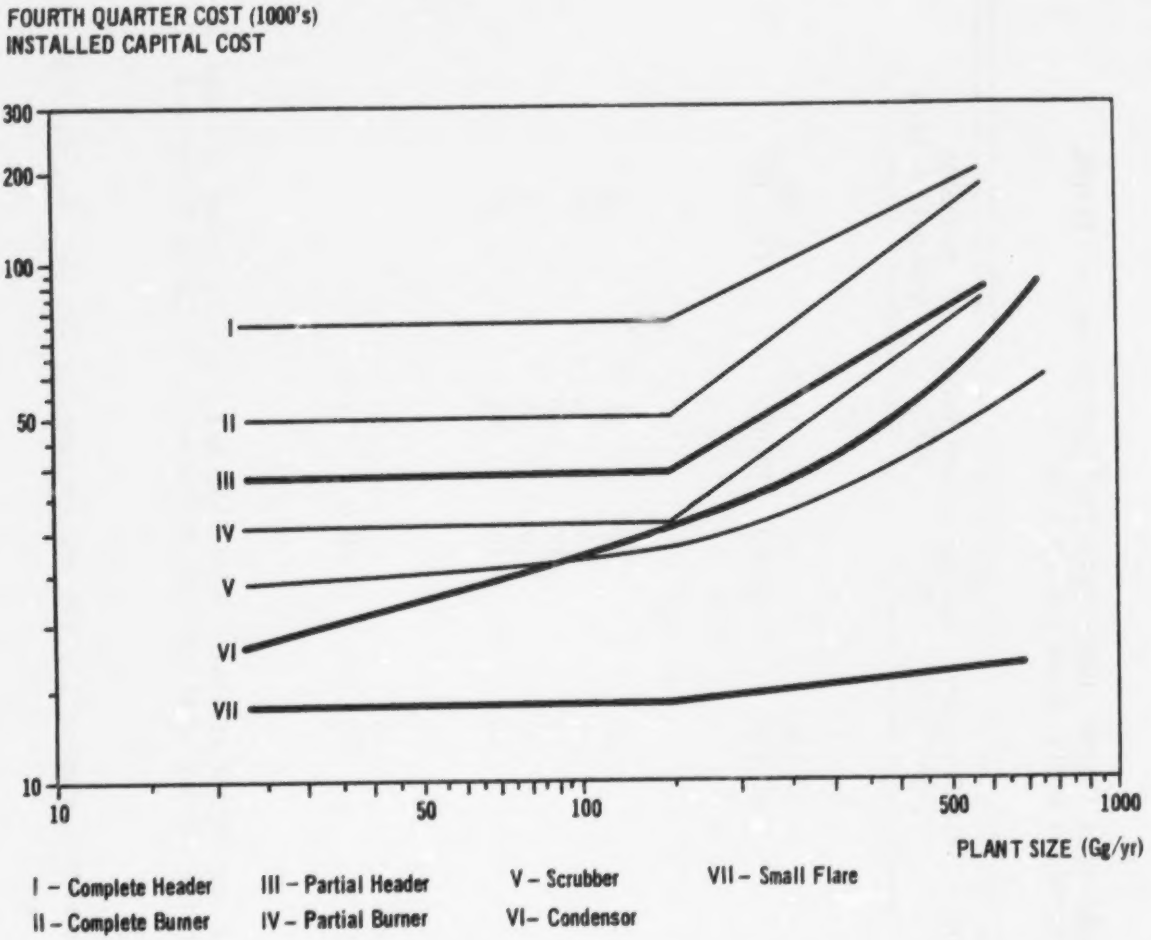
---

[a] The figures are significant to one figure at best. More than one digit is shown in cases to keep the proper ratios between the various vent streams and between the kg/10,000 kg and kg/hr model plant figures.

[b] Benzene/toluene removal column.

[c] Inerts are all other compounds except combustible VOC and include H_2, CO, CO_2, N_2, O_2, and so on.

FIGURE 7–3
CONTROL EQUIPMENT COSTS WITHOUT ALLOWANCES



Based upon scaling of model plant emissions present in Table 7–12.

- Complete header represents the capital cost necessary to pipe all of the vents to the specified control system. This cost will be incurred at facilities practicing little or no control.
- Partial header represents the capital cost necessary to pipe some of the vents to the specified control system. This cost will be incurred at plants currently practicing control of some of the vents.
- Complete burner represents the costs of retrofitting the boiler to accept all of the vents and can include multiple burners and/or compressor/piping systems.
- Partial burner represents the incremental costs of retrofitting the boiler to accept additional uncontrolled vents.
- Scrubber includes the costs of a packed tower, heat exchanger pumps, and piping for control of specified vents.
- Condenser includes two condensers plus piping allowances.
- Compressors and oxygen monitors were considered to cost $30,000 and $23,000, respectively, without allowances, regardless of plant size.

significantly at the small plant sizes. The cost curves for condensers and scrubbers do not show as marked a plateau as do the other pieces of equipment because no minimum size was specified and pilot-sized pieces of equipment can be used.

The capital costs for the flare, burner, and header systems were derived from data presented in the Hydroscience Ethylbenzene/Styrene Product Report.[35] Capital costs for scrubbers and condensers were obtained from vendor data.[36,37] These costs were adjusted to account for installation costs by using installation factors from Reference 38.

7.2.3.3 Annualized Costs

Table 7-13 presents a list of factors that were used to derive the annualized costs for each regulatory option. The total annualized costs of each piece of equipment are made up of operating and maintenance costs, annualized capital costs, and fuel or recovered material credits, if any.

Maintenance costs were estimated as a percentage of total installed capital costs. Supplies (misc. capital) were estimated similarly. Operating costs are made up of electrical power requirements for pumps, compressors, steam, refrigeration, and natural gas. Each of these was assigned a unit value (see Table 7-13). The utility consumption of each device was calculated and summed to yield equipment operating costs. It was assumed that more of the control equipment would require additional operating labor. Flare utility requirements for purge pilot and steam were derived from vendor data.

Benzene credits were calculated assuming a value of $1.00 per gallon ($0.13/lb) for any recovered benzene from the condensers and scrubbers. Each control device was credited with differing degrees of benzene control depending on its assigned efficiency. No credit was given for recovery of other aromatics for ethylbenzene because it was difficult to assign a realistic value to these products. In addition, recovery was assumed to occur for 8,000 hrs/yr.

Fuel recovery credits were estimated by assigning a heating value to each component of the vent gas streams and then assuming that the combined heating value would have the same value ($2.00/MMBtu) as the natural gas it would displace. Total annualized costs for each regulatory option were obtained by annualizing capital costs using a capital recovery factor of 16.25 percent and adding operating and maintenance costs less recovery credits from fuel or material, if applicable.

7.2.4 Plant-By-Plant Costs[39]

7.2.4.1 Introduction

Capital and annualized costs for individual pieces of control equipment were based on the requirements of a model uncontrolled facility. Since each existing facility practices some degree of emissions control, only the incremental costs needed to achieve a given benzene reduction will be considered.

An assessment was made of the equipment that would be needed to achieve a given level of emissions reduction at an uncontrolled facility and this was then used as the basis for deciding what equipment would be needed at existing facilities to achieve the same level of control. Table 7-11 presents the list of equipment that is needed on an uncontrolled plant to achieve the three levels of control specified. Table 7-14 presents the results of the comparison between the existing facilities and the model plant lists and indicates the equipment included in the plant-by-plant cost estimates.

TABLE 7-13. ANNUALIZED COST PARAMETERS[a]

1. Operating factors	8,760 hours per year for utility requirements assuming 100 percent capacity utilization credits 8,000 hours per year for recovery
2. Operating labor	Negligible for flares, condensers, scrubbers, and boilers
3. Maintenance	5% of total installed capital cost
4. Miscellaneous materials	4% of total installed capital cost
5. Utilities:	
Electric power	$8.33/GJ ($0.03/kWh)
Natural gas	$0.071/M^3 ($2.00/1000 scf)
Steam	$0.055/Kg ($2.50/1000 lbs)
Refrigeration	$1.97/GJ ($2.08/MMBtu)
6. Operating materials Polyethylbenzenes for scrubber available at zero cost	
7. Liquid waste disposal	Negligible quantity generated
8. Capital charge rate	16.28% of total installed cost
9. Recovery credits	
Fuel value VOC and benzene using boiler option	$1.894/GJ ($2.00/MMBtu)
Recovered benzene from scrubber and condensers (returned to benzene drying column)	$0.30/Kg ($0.137/lb)

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[a] Values 1, 5, and 8 are used consistently throughout this chapter.

TABLE 7-14. PLANT-BY-PLANT LIST OF EQUIPMENT NEEDED TO ACHIEVE GIVEN REGULATORY OPTIONS

		Control Equipment										
									Oxygen			
Plant & Location	Regulatory Option	Partial Header	Complete Header	Incremental Header	3" Flare	10" Flare	Partial Burner	Complete Burner	Compressor	Monitor	Condenser	Scrubber
Arco, TX	85								X		X	X
Arco, TX	94 Flare		X		X				X	X	X	X
Arco, TX	99 Boiler		X					X		X		
American Hoechst												
New	85										X	
New	94 Flare										X	
New	99 Boiler	X						X		X		
American Hoechst												
Old	85								X		X	X
Old	94 Flare		X		X				X	X	X	X
Old	99 Boiler		X					X		X		
Cos-mar, LA	85								X		X	X
Cos-mar, LA	94 Flare	X			X				X	X	X	X
Cos-mar, LA	99 Boiler	X						X		X		
Gulf Chemicals, TX	85								X		X	X
Gulf Chemicals, TX	94 Flare	X			X				X	X	X	X
Gulf Chemicals, TX	99 Boiler	X						X		X		
Monsanto	85											X
Monsanto	94 Flare		X		X					X		X
Monsanto	99 Boiler		X					X		X		X
Amoco, TX	85								X		X	
Amoco, TX	94 Flare	X			X				X	X	X	
Amoco, TX	99 Boiler	X					X			X		
Dow, TX												
New	85											
New	94 Flare											
New	99 Boiler	X					X			X		
Dow, TX												
Old	85								X		X	X
Old	94 Flare	X			X				X	X	X	X
Old	99 Boiler	X						X		X		
Old	Compressor			X		X						
Sun Oil, TX	85								X		X	
Sun Oil, TX	94 Flare	X			X				X	X	X	
Sun Oil, TX	99 Boiler	X					X			X		
Sun Oil, Tx	Compressor			X								
El Paso, TX	85										X	
El Paso, TX	94 Flare										X	
El Paso, TX	99 Boiler	X					X			X		
Oxirane	85											X
Oxirane	94 Flare										X	X
Oxirane	99 Boiler	X						X		X		
Arco, PA	85								X		X	
Arco, PA	94 Flare	X			X				X	X	X	
Arco, PA	99 Boiler	X					X			X		
U.S. Steel	85											
U.S. Steel	94 Flare											
U.S. Steel	99 Boiler											
Dow Midland	85								X		X	
(Styrene Only)	94 Flare	X			X				X	X	X	
	99 Boiler	X					X			X		

7.2.4.2 Plant-by-Plant Capital Costs

The plant-by-plant capital costs for each regulatory option shown in Table 7-15 were obtained by using the equipment list shown in Table 7-14 in conjunction with the plant size and the individual equipment capital costs presented in Figure 7-3.

The capital costs for each component then were summed and an allowance was added to the installed capital costs to account for indirect costs, such as engineering fees, construction overhead, and contingencies.[38,39] The magnitude of these indirect costs can vary widely and is dependent upon the size, type, and complexity of jobs under consideration. In addition, the contingencies are related directly to the firmness of the cost estimate. Therefore, the absolute magnitude of the indirect costs used by different estimates can vary widely.

7.2.4.3 Plant-by-Plant Annualized Costs and Savings

The plant-by-plant annualized costs for each regulatory option were obtained by summing the individual operation and maintenance costs associated with each piece of equipment shown in Table 7-14 and then adding the annualized capital cost for the control equipment. Any recovery credits that could be assigned for either recovery of heating value or recovery of raw material then were estimated and subtracted from the annualized costs to yield net annualized costs or savings. In several instances, the recovery credits far exceeded the annualized cost of the control device under consideration. However, it must be noted that the amount of savings that could be realized by a given regulatory option will depend upon the actual amount of recoverable material in the controlled stream. For the purpose of this analysis, it was assumed that benzene was the only material of

TABLE 7-15. PLANT-BY-PLANT COSTS

Plant & Location	Option %	Capital Cost (in $1,000)	Annualized Cost (Savings)
Arco, Port Arthur, TX	85	121	(40)
	94 Flare	290	6.5
	99 Boiler	235	(14)
American Hoechst	85	164	(46)
	94 Flare	316	(45)
	99 Boiler	421	(72)
Cos-Mar, LA	85	268	(167.5)
	94 Flare	530	(96)
	99 Boiler	448	(147)
Gulf Chemicals, TX	85	130	(75)
	94 Flare	258	(40)
	99 Boiler	215	(64.5)
Monsanto	85	66	(32)
	94 Flare	325	39
	99 Boiler	424	(76.5)
Amoco	85	72	(28)
	94 Flare	213	13
	99 Boiler	200	7
Dow, TX	85	142	(78)
	94 Flare	387	(28)
	99 Boiler	555	(75)
Sun Oil, TX	85	66	13.5
	94 Flare	173	45
	99 Boiler	130	23
El Paso, TX	85	33	8.5
	94 Flare	33	8
	99 Boiler	130	26
Oxirane	85	243	(172)
	94 Flare	243	(172)
	99 Boiler	366	(119)
Arco, PA	85	74	9.5
	94 Flare	180	38
	99 Boiler	130	27
U.S. Steel	85		
	94 Flare	No additional equipment required.	
	99 Boiler		
Dow, Midland	85	61	(1)
	94 Flare	173	30
	99 Boiler	142	25

value in the vent stream and no recovery credit was given for the other aromatics contained in the vent gases for the model plant. The recovery credits are based upon an average vent stream analysis and recovery occurring 8,000 hrs/yr. The composition of these vent streams will vary from plant to plant and, therefore, the absolute magnitude of the recovery credits also will vary.

Table 7-16 indicates that all three options for controlling the continuous vent streams can result in net revenues for some of the EB/S facilities. The magnitude of the savings is very dependent upon the amount of benzene recovered and the value of the recovered benzene as a feed to process, as well as the heating value of the other organics in the vent stream.

TABLE 7-16. ESTIMATED INDUSTRY-WIDE COST-EFFECTIVENESS FOR EACH REGULATORY OPTION

Option	Annualized Cost (in $1,000) (Savings)	Benzene Removed (Mg)	Cost-Effectiveness Dollars per Mg Benzene (Savings)
85 Percent	$(608.0)	1,225	$(496)
94 Percent	$(201.5)	1,588	$(127)
99 Percent	$(460.0)	1,810	$(254)

This analysis assumed that the benzene which is recovered in the condenser and scrubber system can be fed back into the process via the benzene drying column and that the price of the benzene recovered is the same as its fair market value.

The analysis also assumed that the VOC and benzene that is recovered and used as a fuel in a boiler can be assigned a value comparable with that of natural gas ($2.00/MMBtu).

7.2.5 Cost Comparison and Cost-Effectiveness of the Regulatory Options

7.2.5.1 Costs to Achieve 85 Percent Emissions Reduction

Table 7-16 indicates that, in general, the 85 percent regulatory option requires the smallest capital outlay of any of the three main regulatory options considered. Only one of the 13 facilities under consideration will not have to install any additional equipment to achieve the 85 percent emissions reduction. Capital costs of this option range from zero to $268,000. Total annualized costs of this option range from $13,500 to a savings of $172,000. The range is due to differences in the treatment of the various vent streams in each of the facilities. Some facilities already are controlling those streams which are close to saturation with benzene and which are cost-effective to treat.

7.2.5.2 Costs to Achieve 94 Percent Emissions Reduction

In most cases, the combined scrubber/condenser/flare system requires the largest capital outlay of any of the three options under consideration. This is due to the large amount of piping and equipment required in addition to the flare system (pumps, PEB chillers, scrubbers, condensers, compressors, etc.). One of the 13 facilities can achieve a 94 percent emissions reduction without any capital expenditure. Capital costs for this option range from zero to $530,000. Total annualized costs of this option range from $45,000 to a savings of $172,000. It should be noted that the plant requiring the largest capital expenditure (Cos-Mar) does not have the highest annualized costs; in fact, Cos-Mar exhibits an annual savings of $96,000 under this option. The large range in annualized costs is due to the assumptions regarding the existing degree of control and the amounts of benzene that can be recovered for use as a raw material. Some plants are practicing a high degree of product recovery from the vent streams which are comparatively easy to control. A large capital expenditure is still needed to achieve 94 percent benzene emissions reduction, but very few recovery credits are realized.

7.2.5.3 Costs to Achieve 99 Percent Emissions Reduction

Capital costs for this option range from zero to $555,000. Only one plant has existing control equipment in place which is capable of achieving this level of emissions reduction. Annualized costs of this option range from $26,000 to a savings of $150,000. This range is attributable to the amount of fuel recovery credits assigned to each facility.

7.2.5.4 Cost-Effectiveness of Regulatory Options

The cost-effectiveness of a given regulatory option is defined as the quotient of the total annualized cost of the option and the amount of benzene recovered by the option. This ratio usually is expressed in units of dollars per megagram of benzene recovered. Table 7-16 presents the total annualized cost (or savings), the amount of benzene recovered, and the cost-effectiveness of each regulatory option considered, on a national basis. Because all of the existing facilities practice some degree of control, the amount of benzene recovered by each of the emission options cannot be derived simply from the uncontrolled emissions levels shown in Table 7-12 and the percentages emission reduction specified in the option. Instead, the quantity of benzene recovered is obtained from the incremental level of control between existing levels of control at each facility and the level specified by each of the proposed options.

In addition, the variability in cost-effectiveness between plants for each regulatory option makes it difficult to determine which option is the most cost-effective in aggregate. For this reason, the cost-effectiveness for each option is presented on a national basis.

7.2.6 Costs for Continuous Monitoring

The costs for continuously monitoring benzene emissions are the same for each EB/S plant. The capital costs are based on two gas chromatographs (GC) to measure benzene emissions from a superheater and a boiler. The installed capital cost for the two gas chromatographs is estimated to be $100,000. The total annualized cost of the system is estimated to be $53,000. This includes annualized capital at 16.28 percent, maintenance material, 2.5 percent of installed capital, taxes, insurance, and miscellaneous at four percent, and operating labor at $30,000 per annum. The industry-wide annualized cost of monitoring would be $689,000 for the 13 plants for which costs have been derived.

7.3 OTHER COST CONSIDERATIONS

7.3.1 Introduction

This section presents an estimate of the costs that typical EB/S facilities have to assume in order to comply with other environmental regulations. Currently, in addition to air pollution regulations under consideration, EB/S facilities are faced with compliance with water pollution control regulations and Occupational Safety and Health Administration (OSHA) regulations. In addition, in the near future EB/S facilities will have to comply with regulations concerning control of emissions from storage and handling and fugitive sources.

7.3.2 Water Pollution Control

EB/S facilities are required by the Federal Water Pollution Control Act and Amendments PL 92-500 to apply Best Practicable Control Technology Currently Available (BPCTCA) as of July 1, 1977. In addition, EB/S facilities are required to achieve Best Available Technology Economically Achievable (BATEA) by 1983.

Pursuant to the Act, EPA prepared a document entitled "Development of Effluent Limitations Guidelines and New Source Performance Standards for the Major Organic Products Segment of the Organic Chemicals Manufacturing Point Source Category." The costs presented in this section were taken from this document. The base document presented a range of expected annualized costs for each industrial subcategory.[40]

Due to the wide variations in flow and raw waste loading attributable to each industry in each subcategory, no specific costs for compliance with PL 92-500 were identified for the EB/S industry.

The compliance costs have been determined with respect to the following three levels of technology:

- Best Practicable Control Technology Currently Available (BPCTCA) (1977 standard).
- Best Available Technology Economically Achievable (BATEA) (1983 standard).
- Best Available Demonstrated Control Technology (BADCT) (New Source Performance Standard).

The costs associated with these technologies have been estimated based on model systems which are considered capable of attaining the reduction factors associated with each technology. The particular systems chosen for use in the cost models are not the only systems which are capable of attaining the specified pollutant reductions.

Activated sludge was used as the BPCTCA model treatment system. Dual-media filtration and activated carbon adsorption were used as BATEA. New source end-of-process treatment (BADCT) involves the addition of dual-media filtration to the biological waste treatment model processes.

The general effect of the control techniques is to reduce both the pollutant raw waste load (RWL) and the volume of contact process water discharged for end-of-pipe treatment. It is not possible to recommend a list of process modifications or control measures and associated costs which clearly are applicable to the EB/S industry since the data in Reference 33 are for a group of processes into which the EB/S process falls.

The estimated annualized cost for compliance with water pollution control requirements for the 300,000 Mg/yr (330,000 tons/yr) model plant has been estimated to be:

- For BPCTCA, $130,000 to $810,000.

- For BADCT, $165,000 to $1,100,000.
- For BATEA, $140,000 to $870,000.

These costs are in 1978 dollars based on capital recovery at eight percent, operations computed at two percent of capital, and maintenance computed at four percent of capital.

This cost information is presented in ranges to reflect the variations in flow and RWL given for the process types described in Reference 40.

7.3.3 Storage and Handling Control

EB/S facilities may be required by standards currently under development to control benzene emissions resulting from benzene storage and handling. For the sake of this analysis, it is assumed that the model plant (300,000 Mg/yr) will have two benzene storage tanks of the following sizes:

Tank	Large	Small
Height (m)	12.2	12.2
Diameter (m)	31.0	12.2
Capacity (m^3)	10,000.0	15,000.0

Also, each plant is assumed to have a benzene/toluene tank with the same characteristics as the small benzene tank. These tank sizes are based on data provided in "Emission Control Options for the Synthetic Organic Chemicals Manufacturing Industry, Storage and Handling Report," by Hydroscience, Inc.[41] The number of tanks at each plant was based on trip reports and State EIQ's.[42] Also, it is assumed that for the uncontrolled model plant, the large tank is fitted with an external floating roof with a single seal and the small tank has a fixed roof.

In order to comply with the regulations, the small tank will have an internal floater and the large tank will have a second seal.[43,44] Table 7-17 shows the costs associated with these compliance activities.

7.3.4 Fugitive Emission Control

EB/S facilities may be required by standards currently under development to control fugitive benzene emissions. The draft standards currently require a leak detection and repair program for pipeline, valves, and process drains in benzene service and would require certain equipment, such as double mechanical seals, for pumps, compressors, sampling connections, and open-ended valves in benzene service. The estimated capital and annualized costs for meeting these standards could range from \$57,000 to \$253,000 and from \$14,000 to \$50,000, respectively, for an existing facility.[45]

7.3.5 Compliance With OSHA Regulations

OSHA is charged with the responsibility for developing, promulgating, and enforcing regulations to protect workers against the hazards of toxic materials found in the work place. To this end, the proposed regulation specifies permissible exposure of one ppm in any eight-hour time period, with a ceiling of five ppm averaged over 15 minutes, and additional requirements which are specified in the proposed regulation.

Probable compliance activities have been identified in References 46 and 47 for the EB/S industry and the costs of these activities have been calculated. The computation for costs of compliance under the proposed regulation recognizes only the incremental costs of moving from compliance with the existing benzene regulation (29 CFR 1910.1000) to compliance with the new regulation.

TABLE 7-17. STORAGE EMISSION CONTROL COSTS FOR EACH TANK[43,44]

Tank Size m^3	Control Technology	Installed Capital Costs ($1,000)	Annual Operating Costs ($1,000)	Annual Recovery Credit ($1,000)	Total Annualized ($1,000)
1,500	a	42.0	11.5	18.00	(0.33)
	b	27.0	6.4	18.00	(7.60)
10,000	c	8.5	2.2	1.26	2.20
	d	14.5	3.4	1.26	4.30

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[a] Fixed roof tank retrofitted with floating roof.

[b] Incremental cost of new internal floating roof versus new fixed roof.

[c] Secondary seals installed on open-top floating roof tanks -- new.

[d] Secondary seals installed on open-top floating roof tanks -- retrofit.

There are alternative methods available to employers for complying with the proposed OSHA regulation. However, under the scope of this analysis, only the least cost method of compliance is attributed to the proposed regulation.

Operating costs for compliance during the first year are those associated with exposure measurements, respirators, personal controls, recordkeeping, medical surveillance, employee training and information, and signs and labels.[46] For the model plant, this costs \$18,200. At this level, the total EB/S industry costs will be \$308,000. Recurring costs are similar in nature but reflect reduced usage of respirators and a less vigorous monitoring program. These costs have been estimated to be \$10,200/yr for the model plant and \$173,000/yr for the total EB/S industry. These costs are based on the assumption that at the model EB/S plant there are 32 persons exposed to benzene and that industry-wide there are 540 persons exposed to benzene. Additional basis for the costs of compliance are shown in Table 7-18.[47]

The capital costs for compliance with the OSHA regulations are those to rebuild both pumps and compressors, install rupture discs or similar devices in vent systems, improve maintenance of pipeline valves, improve procedures for transferring and storing benzene, install automatic fill monitoring devices, and initiate procedures for closed system sampling. These capital costs are included as part of the costs of compliance with the fugitive and storage and handling regulations and are not included as costs of compliance with OSHA regulations.

TABLE 7-18. COST BASIS FOR CALCULATIONS OF OPERATING COSTS

Exposure Measurements	Costs
Measurement Equipment	
Pump, Sipin, Model SP2, 20-100 cc/min	$328/facility
Charger	$ 20/facility
Calibration Kit	$ 98/facility
Measurements	
Charcoal tube	$.71/charcoal tube
Analysis	$ 35/charcoal tube
Notification	$ 2/measurement
Medical Surveillance	
Initial Exam	$ 68/exam
Incremental Exam	$ 48/exam
Respirators	
Half-facepiece chemical cartridge respirator without cartridge (MSA Cat. No. 460968) Comfo Respirator	$8.85/respirator
GMA cartridge for Comfo Respirator (MSA Cat. No. 459315)	$2.04/cartridge
Full facepiece chemical cartridge respirator without cartridge	$63.00/respirator
Personal Protection Equipment	
Gloves, Apron, Faceshield, Goggles	$13.16/employee
Training Costs	
Preparation	$110/facility
Training	$ 14/employee
Signs & Labels	
Labels	$14.75/100 labels
Signs	$22.50/signs
Labor	
Clerical	$ 8/hr
Employer	$20/hr
Employee	$10/hr

7.4 ECONOMIC IMPACT ANALYSIS

Four control strategies exist for reducing benzene emissions in the EB/S industry. Three options, the 85 percent scrubber/condenser system, the 94 percent flare, and the 99 percent boiler regulatory option, represent control levels which can be achieved through existing technologies. The potential impacts of these control strategies will be analyzed in Sections 7.4.1 through 7.4.3. The analysis, which is based on plant-by-plant costs presented in Section 7.2, highlights differential impacts across producing firms. It is recognized that differentials in production economies exist for these firms. Differences in fuel, feedstock, and transportation costs per unit of output can be sizable. However, the focus in this report is on differential impacts of controls, since these impacts may either mitigate or exacerbate production cost differentials. The fourth regulatory option, 100 percent control, cannot be achieved through any existing technology. Such control would require the closure of all styrene plants. The potential impact of this option is analyzed in Section 7.4.4.

7.4.1 Control Costs and Feasibility

7.4.1.1 Costs of Control by Regulatory Option

Tables 7-19, 7-20, and 7-21 present capital and total annualized costs of control by firm for the 85, the 94, and the 99 percent options, respectively. Cost estimates vary considerably across firms. Capital costs per firm range from lows of zero (under all options) to highs of $268,000, $560,000, and $697,000 under the 85, 94, and 99 percent controls, respectively. While Dow Chemical experiences the largest capital costs, its capital costs per Mg of capacity are moderate. Comparable estimates for Sun

TABLE 7-19. COST SUMMARY: 85 PERCENT REGULATORY OPTION

Producing Company	Capital Cost ($1,000)	Capital Cost per Mg Capacity[a] ($/Mg)	Total Annualized Cost ($1,000)	Total Annualized Cost per Mg Capacity[a] ($/Mg)
American Hoechst Corp.	164	0.36	-46.0	-0.10
Amoco	72	0.19	-28.0	-0.07
Atlantic Richfield Co. (2 locations)	195	0.98	-30.5	-0.15
Cos-Mar, Inc.	268	0.45	-167.5	-0.28
Dow Chemical, USA (2 locations)	203	0.24	-79.0	-0.09
El Paso Products Co.	33	0.29	8.5	0.07
Gulf Oil Corporation	130	0.48	-75.0	-0.28
Monsanto Company	66	0.10	-32.0	-0.05
Oxirane Corporation	243	0.54	-172.0	-0.38
Sun Oil Company	66	1.83	13.5	0.38
United States Steel	0	0	0	0
Total Industry	1,440	0.35	-608.0	-0.15

[a] Styrene capacity given in Table 7-1.

TABLE 7-20. COST SUMMARY: 94 PERCENT REGULATORY OPTION

Producing Company	Capital Cost ($1,000)	Capital Cost per Mg Capacity[a] ($/Mg)	Total Annualized Cost ($1,000)	Total Annualized Cost per Mg Capacity[a] ($/Mg)
American Hoechst Corp.	316	0.70	-45.0	-0.10
Amoco	213	0.56	13.0	0.03
Atlantic Richfield Co. (2 locations)	470	2.35	44.5	0.22
Cos-Mar, Inc.	530	0.90	-96.0	-0.16
Dow Chemical, USA (2 locations)	560	0.65	2.0	0.002
El Paso Products Co.	33	0.29	8.0	0.07
Gulf Oil Corporation	258	0.95	-40.0	-0.15
Monsanto Company	325	0.48	39.0	0.06
Oxirane Corporation	243	0.54	-172.0	-0.38
Sun Oil Company	173	4.81	45.0	1.25
United States Steel	0	0	0	0
Total Industry	3,121	0.76	-201.5	-0.05

[a] Styrene capacity given in Table 7-1.

TABLE 7-21. COST SUMMARY: 99 PERCENT REGULATORY OPTION

Producing Company	Capital Cost ($1,000)	Capital Cost per Mg Capacity[a] ($/Mg)	Total Annualized Cost ($1,000)	Total Annualized Cost per Mg Capacity[a] ($/Mg)
American Hoechst Corp.	421	0.94	-72.0	-0.16
Amoco	200	0.53	7.0	0.02
Atlantic Richfield Co. (2 locations)	365	1.82	13.0	0.06
Cos-Mar, Inc.	448	0.76	-147.0	-0.25
Dow Chemical, USA (2 locations)	697	0.81	-50.0	-0.06
El Paso Products Co.	130	1.13	26.0	0.23
Gulf Oil Corporation	215	0.79	-64.5	-0.24
Monsanto Company	424	0.62	-76.5	-0.11
Oxirane Corporation	366	0.81	-119.0	-0.26
Sun Oil Company	130	3.61	23.0	0.64
United States Steel	0	0	0	0
Total Industry	3,396	0.83	-460.0	-0.11

[a] Styrene capacity given in Table 7-1.

Oil Company are somewhat larger, approximately twice that of the next highest company estimate. Capital cost per Mg is also fairly high for Atlantic Richfield. Both capital and capital cost per Mg are lowest (at zero) for United States Steel.

Industry-wide total annualized costs are actually net credits of $608,000, $202,000, and $460,000 for the 85, 94, and 99 percent options, respectively. However, under all options some companies experience net costs, not net credits. Two firms face positive annualized costs under the 85 percent regulatory option. Six firms experience net costs under the 94 percent control as do four companies under the 99 percent option. The maximum value of such costs is $45,000 for Sun Oil Company under the 94 percent regulatory option.

7.4.1.2 Feasibility of Financing

There are several reasons for believing that EB/S producers should have little difficulty meeting the capital requirements of proposed controls. Note that representative company capital expenditures shown in Table 7-22 are very much larger than the capital costs of control shown in Table 7-19 through Table 7-21. Control expenditures are well within the scope of normal spending.

Moreover, financial information presented earlier (Table 7-9) indicates that parent companies should have little difficulty with either debt or equity financing. Debt-equity ratios are sufficiently low that borrowing should present no problems. Rates of return on equity are sufficiently high that equity financing should not be difficult either.

Whether the affected companies will choose to finance controls and continue operating is a more difficult question. The choice to finance will depend critically upon the age of the plant in question, the impact of

TABLE 7-22. REPRESENTATIVE CAPITAL EXPENDITURES[28]

Company	Year	Expenditure (in $1,000)	Comment
American Petrofina (joint owner, Cos-Mar)	1977	60,189	Capital expenditures and property acquisitions; all lines of business
Amoco	1977	269,839	Capital expenditures in Chemical Operations
Atlantic Richfield	1977	278,000	Capital expenditures in Chemical Operations
Dow Chemical, USA	1977	1,163,016	Capital expenditures; all lines of business
El Paso Products	1975	445,081	New property, plant and equipment; all lines of business
Gulf Oil	1977	174,000	Capital expenditures in Chemical Operations
Monsanto	1977	607,100	Capital expenditures; all lines of business
United States Steel	1977	864,700	Capital expenditures; all lines of business

control costs on plant and company profitability, and the other investment options available to the company. As all EB/S producers are diversified companies, investment alternatives may be very important. While it is not possible to make any definitive statements with regard to investment alternatives, it is possible to assess the impacts of controls on company profitability under some assumptions with regard to plant age. These impacts will be addressed in the analysis which follows.

7.4.2 Economic Impact Methodology

7.4.2.1 Pricing Scenarios

The impacts of proposed emission control regulations on individual firms and on the economy as a whole will depend upon the degree to which cost increases are accompanied by price increases. Consequently, impacts are analyzed under two alternative firm pricing assumptions. These assumptions are full cost absorption and full cost pricing.

Under full cost absorption, an affected firm bears the entire incremental cost of emission controls. Output price does not increase and control costs cannot be passed back onto resource suppliers. The result is a lower rate of return on investment. This scenario generally is associated with strong market competition. Excess capacity in the industry, the existence of close product substitutes, or the presence of strong international competition can result in full cost absorption. This scenario generates maximum impacts for individual companies and minimum (zero) inflationary impacts.

Under full cost pricing, the affected firm sets a new price so as to maintain a target rate of return on investment. Again, the firm is assumed to be unable to pass costs back to resource suppliers. However, the firm can pass costs forward. Higher prices will be accompanied by a smaller quantity sold and consequently lower industry-wide output and employment. Full cost pricing generally is associated with a constant cost industry and/or minimal competition from other products or other producing nations. Full cost pricing generates maximal inflationary impacts and minimal individual firm impacts.

Full cost absorption and full cost pricing are intended to represent extreme situations which may occur; either is actually possible in the EB/S industry. The existence of excess capacity would mitigate against cost pass through (full cost pricing) currently. But to the degree that higher operating rates are achieved over the next few years, pass through will be more feasible. Some styrene substitutes exist, but they are not perfect substitutes. Styrene can be imported, but transportation costs and higher foreign feedstock and energy costs exist. The result is some room for price increases. However, it is clear that increases will be limited by the threat of product substitution and/or importation.

Thus, depending upon capacity utilization and the availability of substitutes, actual impacts may range anywhere from full cost absorption to full cost pricing. The price, output, and employment impacts generated under full cost pricing and the profitability impacts generated under full cost absorption are maximum likely changes. All maximum impacts do not occur simultaneously. Any price increase means a smaller impact on profitability, just as any cost absorption means a smaller impact on price, output, and employment.

7.4.2.2 Economic Conditions

As noted previously, an industry's ability to pass forward costs depends upon capacity utilization. Excess capacity, which inhibits cost pass through, currently exists in the EB/S industry. Consequently, all impacts are assessed under two scenarios: 76 percent capacity utilization (the current level) and 100 percent utilization. Price changes calculated with the 100 percent utilization assumption have a higher probability of occurrence than do those calculated with the 76 percent utilization assumption. Rate of return impacts (with price unchanged) are most likely with the 76 percent utilization scenario.

Impacts also are estimated with two different target rates of return: six percent (as a lower bound) and 15 percent (as a realistic rate). As impacts are larger in magnitude under the 15 percent target, only these results are presented.

All impacts are based on the same assumptions with regard to product price ($463 per Mg), tax rate (46 percent), and equipment life (ten years). Note that an equipment life of ten years corresponds to the capital recovery factor used to calculate annualized costs in Section 7.2. If equipment life is actually greater than ten years, impacts will be overestimated. Since equipment life is not likely to be less than ten years, impact estimates can be regarded as worst case calculations.

7.4.2.3 Estimation Procedure: Simple Rate of Return Impacts Under Full Cost Absorption

Under full cost absorption it is assumed that firms do not pass cost changes into price changes. Consequently, there are no effects on output or employment. Instead, cost changes result in changes in the rate of return on investment. Assuming simple rate of return analysis, the impact on the firms' rate of return on investment is given by the following equation:

$$\Delta r = - \frac{r \cdot \Delta K + (1-t)\ \Delta TOC}{K + \Delta K} \qquad (2)$$

where

Δr = change in rate of return on investment

ΔTOC = total annual operating costs of the control equipment

ΔK = total costs (acquisition and installation) of the control equipment

K = precontrol level of capital investment

r = target rate of return

t = tax rate

Note that total annual operating costs (ΔTOC) include an allowance for the depreciation of control equipment in addition to regular operating expenses. Annual depreciation is estimated to be ten percent of total acquisition and installation costs based on an assumption of straight-line depreciation over a ten-year life. Note also that this formulation can be used to estimate impacts either on the rate of return to an individual plant or on the rate of return to firm equity, with the value of K determined accordingly.

This analysis will focus on simple rates of return to equity. An equity base was chosen for two reasons. Rates of return to specific existing plants require more detailed information on specific plant values than is immediately available. Approximations of these values could have been made, but they would have been very rough. In addition, it is not clear that rates of return to specific plants are preferable on theoretical grounds when applied to an integrated operation. As noted previously, many affected firms produce their own feedstocks and/or styrene derivatives. Theoretically, base rates of return and impacts should be calculated on the entire extended operation, not just on the individual styrene plant. However, this requires a great deal of specific information which is not available. Rates of return on equity are taken as a proxy for rates of return to extended (vertically integrated) operations. Given the lack of data and the nature of the estimate (as a proxy), it did not seem valid to apply a more sophisticated methodology than a simple rate of return analysis.

7.4.2.4 Estimation Procedure: Price Impacts Under Full Cost Pricing

Under full cost pricing, the firm is assumed to react to cost changes by adjusting output price in order to maintain some specific target rate of return on investment. The required price change (ΔP) is given by the following equation:

$$\Delta P = \frac{\Delta TOC + r \cdot \Delta K/(1-t)}{C \cdot Q} \quad (3)$$

where ΔP denotes the required product price change, Q denotes the firm's production capacity, and C refers to capacity utilization. (All other variables are defined in the preceding section.)

Capacity utilization is assumed to be unchanged by the imposition of controls. But a price increase results in a smaller quantity demanded from the industry. Obviously, not all companies will be able to maintain capacity utilization. The highest cost company may experience the entire output impact or various companies may share the impact. A sharing of the impact cannot be analyzed without a much more complex model.

7.4.2.5 Other Economic Impacts

The price and rate of return impacts estimated in accordance with the preceding methodology are used to make quantitative and qualitative assessments of additional economic impacts. Maximal price changes together with elasticity estimates (Section 7.1) can be used to estimate maximal output and hence employment impacts. Rate of return impacts potentially affect new investment in the industry. These impacts also are considered.

7.4.2.6 Data

Total costs of control equipment (ΔK) and total annual operating costs (ΔTOC) are derived from information in Section 7.2. For rate of return impacts, equity values (K) are obtained from Securities and Exchange Commission 10K Forms. Production capacities (Q) are taken from the 1978 Directory of Chemical Producers (SRI International). Capacity utilization is set at either 76 percent (the current estimate) or 100 percent (for full pass through).

7.4.3 Economic Impacts

7.4.3.1 Rate of Return Impacts

Table 7-23 presents estimates of impacts on rates of return on equity under full cost absorption for the 85, 94, and the 99 percent regulatory options, respectively. Note that while all estimated impacts are small, they may be either negative (decreasing the rate of return) or positive (increasing the rate of return). Positive impacts can occur because controls sometimes result in operating cost savings (negative ΔTOC). If operating cost savings are sufficiently large relative to capital expenditures, the net impact on the rate of return will be positive. Note that although the procedure for calculating rate of return impacts combines operating and capital costs in a somewhat different manner, the same principle which results in negative total annualized costs results in positive rate of return impacts.

All rate of return impacts are small. Under the 85 percent regulatory option, the maximum negative impact is -0.000011 (-0.01 percent of the 15 percent target) for El Paso Products Company, while the average of firm impacts is 0.000013 (0.01 percent of the target). The maximum positive impact is 0.000111 (0.07 percent of the target) for American Petrofina. Under the 94 percent regulatory option, the maximum negative impact is -0.000020 (0.01 percent of target) for Monsanto. The average of firm impacts is -0.000007 (0.005 percent of target). Only Borg-Warner experiences a positive impact on rate of return (0.000001). Under the 99 percent regulatory option, the maximum negative impact is -0.000038 (0.03 percent of target) for El Paso Products while the maximum positive impact is 0.000063 for American Petrofina. The average of firm impacts is -0.000005 (0.005 percent of the target).

In terms of both averages and maximum impacts it is clear that the 94 percent regulatory option produces the largest impacts on rates of return. While these impacts average less than 0.01 percent of the target rate of return, it is clear that impacts differ across firms. Borg-Warner shows small positive impacts under all regulatory options. Gulf Oil experiences relatively small impacts under all regulatory options. El Paso Products sustains relatively large impacts under all regulatory options. However, these impacts are large only in a relative sense and represent a maximum of 0.04 percent of the target rate of return. Substantial impacts on the industry are not anticipated.

7.4.3.2 Price Impacts

Tables 7-24 through 7-26 present price changes required to maintain a 15 percent target rate of return under three regulatory options and two capacity utilization scenarios. As with rate of return impacts, price changes required by individual firms may be either positive or negative. The direction of the change will depend upon the interplay of capital costs and operating cost savings.

While all indicated price changes are small in magnitude and percentage terms, those required under 76 percent utilization (the current figure) are the largest. These required price changes are estimated specifically to obtain an indication of maximum impacts. However, one simply cannot take the maximum of these required price changes (for any control option) and consider that change to be a reasonable expected price increase. Such a figure would overestimate the degree to which costs can be passed forward in the presence of excess capacity.

TABLE 7-23. RATE OF RETURN ON EQUITY IMPACTS[a]

Parent Company	85% Control		94% Control		99% Control	
	ΔROR	ΔROR/ ROR (%)	ΔROR	ΔROR/ ROR (%)	ΔROR	ΔROR/ ROR (%)
American Petrofina (joint owner, Cos-Mar)	.000111	0.07	-.000003	-0.00	.000063	0.04
Amoco	.000002	0.00	-.000006	-0.00	-.000005	-0.00
Atlantic Richfield (ARCO & joint owner, Oxirane)	.000006	0.00	-.000006	-0.00	-.000026	-0.02
Borg-Warner (joint owner, Cos-Mar)	.000022	0.01	.000001	-0.00	.000012	0.01
Dow Chemical, USA	.000007	0.00	-.000016	-0.01	-.000012	-0.01
El Paso Products Co.	-.000011	-0.01	-.000011	-0.01	-.000038	-0.03
Gulf Oil Corporation	.000004	0.00	-.000000	-0.00	.000002	0.00
Monsanto Company	.000004	0.00	-.000020	-0.01	-.000000	-0.00
Sun Oil Company	-.000005	-0.00	-.000014	-0.01	-.000008	-0.01
United States Steel	0.00	0.00	0.00	0.00	0.00	0.00

[a] Impacts on rates of return on equity are estimated for those parent companies for which financial data were available. A 15 percent target rate of return is assumed.

TABLE 7-24. REQUIRED STYRENE PRICE CHANGES: 85 PERCENT CONTROL[a]

	76% Capacity Utilization		100% Capacity Utilization	
Producing Company	ΔP ($/Mg)	ΔP/P[b] (%)	ΔP ($/Mg)	ΔP/P[b] (%)
American Hoechst Corp.	-0.05	-0.01	-0.04	-0.01
Amoco	-0.05	-0.01	-0.04	-0.01
Atlantic Richfield Co. (2 locations)	0.02	0.00	0.02	0.00
Cos-Mar, Inc.	-0.27	-0.06	-0.20	-0.04
Dow Chemical, USA	-0.07	-0.02	-0.05	-0.01
El Paso Products Co.	0.16	0.03	0.12	0.03
Gulf Oil Corporation	-0.25	-0.05	-0.19	-0.04
Monsanto Company	-0.04	-0.01	-0.03	-0.01
Oxirane Corporation	-0.38	-0.08	-0.29	0.06
Sun Oil Company	0.91	0.20	0.70	0.15
United States Steel	0.00	0.00	0.00	0.00

[a] Price changes required to maintain a 15 percent rate of return are presented.

[b] Percentage price change calculations assume a base price of $463 per Mg.

TABLE 7-25. REQUIRED SYTRENE PRICE CHANGES: 94 PERCENT CONTROL[a]

Producing Company	76% Capacity Utilization		100% Capacity Utilization	
	ΔP ($/Mg)	ΔP/P[b] (%)	ΔP ($/Mg)	ΔP/P[b] (%)
American Hoeschst Corp.	0.03	0.01	0.02	0.00
Amoco	0.17	0.04	0.13	0.03
Atlantic Richfield Co. (2 locations)	0.83	0.18	0.63	0.14
Cos-Mar, Inc.	0.01	0.00	0.01	0.00
Dow Chemical, USA (2 locations)	0.15	0.03	0.12	0.03
El Paso Products Co.	0.16	0.03	0.12	0.03
Gulf Oil Corporation	0.02	0.00	0.02	0.00
Monsanto Company	0.19	0.04	0.14	0.03
Oxirane Corporation	-0.38	-0.08	-0.29	-0.06
Sun Oil Company	2.82	0.61	2.14	0.46
United States Steel	0.00	0.00	0.00	0.00

[a] Price changes required to maintain a 15 percent rate of return are presented.

[b] Percentage price change calculations assume a base price of $463 per Mg.

TABLE 7-26. REQUIRED STYRENE PRICE CHANGES: 99 PERCENT CONTROL[a]

	76% Capacity Utilization		100% Capacity Utilization	
Producing Company	ΔP ($/Mg)	$\Delta P/P$[b] (%)	ΔP ($/Mg)	$\Delta P/P$[b] (%)
American Hoeschst Corp.	0.00	-0.00	0.00	0.00
Amoco	0.15	0.03	0.11	0.02
Atlantic Richfield Co. (2 locations)	0.51	0.11	0.38	0.08
Cos-Mar, Inc.	-0.15	-0.03	-0.12	-0.03
Dow Chemical, USA (2 locations)	0.11	0.02	0.08	0.02
El Paso Products Co.	0.56	0.12	0.42	0.09
Gulf Oil Corporation	-0.13	-0.03	-0.10	-0.02
Monsanto Company	0.00	0.00	0.00	0.00
Oxirane Corporation	-0.16	-0.03	-0.12	-0.03
Sun Oil Company	1.67	0.36	1.27	0.27
United States Steel	0.00	0.00	0.00	0.00

[a] Price changes required to maintain a 15 percent rate of return are presented.

[b] Percentage price change calculations assume a base price of $463 per Mg.

Consider the following example, which assumes implementation of the 85 percent regulatory option. The largest required price change under this option is $0.91/Mg for Sun Oil Company. Since no other company requires this large a price increase, the operative question becomes whether Sun Oil could implement this increase and still sell its product. At 76 percent utilization, current domestic styrene capacity of 4,092,000 Mg/year corresponds to production of 3,110,000 Mg/year. This production level could be met without any output from Sun Oil's 36,000 Mg/year plant. If the other producers chose not to match Sun Oil's new price, styrene would not sell at that higher price. The next largest required price increase is $0.16/Mg for El Paso Products. But El Paso's capacity is only 115,000 Mg/year. Both Sun Oil and El Paso could be undercut by other firms at this price without creating capacity problems.

In the absence of collusion among producers, maximum required price increases under 76 percent utilization could not hold. As noted previously, excess capacity generally inhibits full cost pricing. Consequently, all further discussion of price increases will be based on the assumption of 100 percent utilization.

Required price changes vary with the regulatory option selected. The averages of required price changes are $0.0/Mg, $0.28/Mg, and $0.17/Mg for the 85, 94, and 99 percent regulatory options, respectively. Note that required increases are greatest under the 94 percent regulatory option. The maximum required price increase under that option is $2.14/Mg (0.46 percent of product price). The smallest required increases are under the 85 percent scrubber/condenser system.

Required price changes vary across companies also. Assuming 100 percent utilization, price increases required under the 85 percent regulatory option range from -$0.29 (Oxirane) to $0.70 (Sun Oil). Under the 94 percent option the range is from -$0.29 (Oxirane) to $2.14 (Sun Oil) and under the 99 percent control it is from -$0.12 (Oxirane, Cos-Mar) to $1.27 (Sun Oil). Only Oxirane faces negative required price changes under all potential regulatory options. Three companies (Atlantic Richfield, El Paso Products, and Sun Oil) experience positive required price increases under all regulatory options. The maximum increase required under any option for any company is $2.14 or 0.46 percent of product price.

7.4.3.3 Output and Employment Impacts

Assuming 100 percent capacity utilization and a 15 percent target rate of return, the 85 percent regulatory option generates a maximum required increase of $0.70/Mg (0.15 percent of product price). Assuming a long-run price elasticity of 0.49 (see Section 7.1), this maximum price increase corresponds to a maximum potential demand decrease of 0.07 percent, which corresponds to 2.3 thousand Mg at the current production level and 2.9 thousand Mg at the projected 1983 output level. Based on employment data from Section 7.1, this corresponds to a maximum of one worker displaced.

Under the same assumptions, the 94 percent regulatory option generates a maximum price increase of $2.14/Mg (0.46 percent of price), which corresponds to an output decrease of 7.0 thousand Mg at the current production level and 9.0 thousand Mg at the projected 1983 level. A maximum of fewer than three workers should be displaced. Under the 99 percent regulatory option, the maximum price increase required is $1.27/Mg (0.27 percent of price), which corresponds to an output decrease of 4.1 thousand Mg at the current production level and 5.3 thousand Mg at the projected 1983 level. Fewer than two workers should be displaced.

Note that the employment impacts cited above are maximum values corresponding to maximum price increases. Actual increases may not be as large. Also, these employment impacts do not include jobs created by the regulatory options. Operation and maintenance of control systems would require more labor time than would be displaced by the output decreases estimated. Net employment impacts under each of the options considered probably would be positive but small in any case.

7.4.3.4 Investment Impacts

It is unlikely that any of the regulatory options considered in this report would have a substantial impact on investment in styrene production. A typical new styrene plant is estimated to cost upwards of $60 million.[48] The capital costs of control for any single existing plant are less than one percent of this base plant cost and control costs in a new plant would probably be lower, as retrofits are generally more expensive. Moreover, these capital costs are offset partly by operating cost savings. No major investment impacts are anticipated.

7.4.3.5 Interindustry Impacts

Interindustry impacts would be negligible under full cost absorption. Under full cost pricing, some demand decrease could be expected. This decrease would correspond to a decrease in demand for styrene derivatives. Some impact thus would be felt by the producers who further fabricate styrene. However, since styrene cost represents only a minor portion of the market price of the final goods produced, such impacts would be quite small.

Similarly, there probably will be some substitution of other products for styrene-produced goods. But substitution would be small and would be spread over a number of basic substitute chemicals. Consequently, little impact is expected on overall plastics or resin material prices.

7.4.3.6 Impact Summary

Impacts on rates of return on equity under full cost absorption are small. The largest adverse impact is -0.000038 or 0.03 percent of the target rate of return of 15 percent. Impacts are generally largest under the 94 percent regulatory option and smallest under the 85 percent option.

Price increases required to maintain a target rate of return (full cost pricing) are also largest under the 94 percent regulatory option. If 100 percent utilization is assumed, the average required price increase is \$0.28/Mg. The maximum required price increase for any individual firm is \$2.14/Mg (0.46 percent of product price). The output decrease which is estimated to correspond with this maximum price increase is approximately 0.23 percent. This would represent 7.0 thousand Mg at the current production level and 9.0 thousand Mg at the projected 1983 production level. Employment cutbacks associated with decreased output probably would be outweighed by the labor requirements associated with controls. Substantial impacts on new investment are not anticipated. Also, interindustry impacts should be small.

7.4.4 100 Percent Control (Zero Emissions): The Closure Option

A zero emission limitation is the only emission standard which would provide absolute safety with regard to benzene emissions. However, no currently available control technology will guarantee zero emissions. Zero emissions would require a ban on domestic production of styrene. The full impact of such a ban would depend upon whether domestic production of styrene derivatives could continue.

If styrene monomer could be imported in sufficient quantities, styrene derivative production could continue in the United States. Moreover, the production of final goods containing styrene could remain unchanged under such import conditions. While increased material transportation costs would increase the prices of styrene products, rendering them less competitive, they could continue to be marketed. Unfortunately, the availability of large quantities of styrene monomer for import is highly questionable. The United States traditionally has been a net exporter of styrene, with facilities representing approximately 40 percent of total world capacity. It is unlikely that sufficient imports would be available in the near future. In the long term, foreign producers might choose to further process the monomer themselves, making styrene derivatives rather than styrene available for world consumption. Accordingly, the potential impact of closing styrene derivative plants as well as styrene monomer facilities must be assessed.

In the following analysis we consider the direct impacts of closing styrene monomer and styrene derivative facilities. The indirect effects of such closures on material suppliers and intermediate consumers are addressed also. In addition, the existence and availability of substitutes for styrene in final goods production are considered.

7.4.4.1 Direct Impacts

Styrene is produced by 11 companies at 12 locations in the United States. In 1978, domestic styrene production was valued at $1,135 million. Direct employment in the industry is estimated to be 650 to 950 workers. Production facilities are concentrated geographically in Louisiana and Texas. In these areas there would be a multiplier effect associated with decreased output, increased unemployment, and lower overall income if styrene production were discontinued.

There is considerable investment embodied in existing styrene facilities. As the potential loss for the owners of these facilities is sizable, an estimate of the value of existing investments in styrene production must be made. Several general methods of estimation were employed to arrive at approximations of styrene asset values.

The first method of estimation utilizes published information for SIC 2865, Cyclic Crudes and Intermediates. (In 1978, the value of styrene production accounted for 24 percent of the value of shipments for SIC 2865.) This method of estimation relies upon the assumption that the value of assets per dollar of output is uniform across SIC 2865. Under this methodology, investments in styrene are estimated to be worth approximately $925 million.

Of course, the value of assets per dollar of output is not necessarily uniform across the overall industry. A second estimate was constructed utilizing limited information specific to styrene which is available. This methodology employs engineering estimates of costs for typical new plants in 1970[48] which are updated to 1978 through a price index for producer capital goods. Historical information from the Chemical Economics Handbook is used to estimate the ages of existing plants.[29] Under this methodology, investments in styrene are estimated to be between $400 million and $500 million.

Note that the SIC methodology produces an estimate which is twice as large as the more specific estimate. Since assumptions and approximations are involved in each estimation, it is not possible to say which is closer to the truth. However, since the SIC methodology is the best available for some subsequent estimations, it should be noted that this methodology may result in high-side approximations.

Styrene plastics materials (the intermediate product derivatives) are produced by more than 40 companies throughout the United States. In 1978, production of styrene plastics materials was valued at $1,812 million. Under a procedure similar to the SIC method described above, employment for this industry is estimated to be over 11,000 total workers, including more than 7,000 production workers.

Investments in the production of styrene plastics materials also are approximated through the SIC methodology. Asset values are estimated to total $1,236 million. Styrene monomer and styrene plastics materials together account for $2.16 billion worth of assets under this methodology. As noted, this may be a high side estimate, but the true value is certainly likely to be more than $1 billion.

The explicit impact on the producing companies of banning styrene manufacture is difficult to assess without detailed profit data. Production values and overall sales data can be used to produce a proxy for the importance of styrene to overall profitability, but such approximations can be misleading for several reasons. First, not all sales are equally profitable. Percentage contribution to revenues can differ considerably from percentage contribution to profits. Moreover, as shown in Table 7-8, many styrene producers market styrene derivatives and produce styrene feedstocks. If derivative production in the United States is discontinued, the impact on individual styrene producers may be larger than the impact captured by styrene production values.

As an example, styrene sales account for only two percent of Monsanto's total sales. Yet 60 percent of styrene produced is captively consumed, which means that the value of styrene production is approximately five percent of sales. However, Monsanto reports that if derivative production is considered, 25 percent of total sales is the appropriate figure.[49] Even for a large, highly differentiated company, a loss of 25 percent of sales revenues is difficult to absorb.

The question of direct closure could depend critically on the survival of domestic derivative production. If only styrene monomer production were to cease, direct closures most likely would be limited to the two operating companies, Cos-Mar and Oxirane. These companies produce nothing but styrene. However, the parent companies of Cos-Mar (American Petrofina and Borg-Warner) and Oxirane (Atlantic Richfield and Halcon International) are large, multi-product producers. Their failure is unlikely.

However, the degree of vertical integration in the chemical industry indicates that substantial reduction in the production of styrene derivatives would increase greatly the impact on styrene-producing companies. This impact might be mitigated by the fact that a number of the producers of styrene derivatives also produce potential substitutes for those derivatives. However, loss of revenues due to styrene closures would put them in a disadvantageous position vis-a-vis other producers of substitutes in expanding the production of substitutes. Consequently, these companies actually could experience an additional adverse impact in the form of decreased market share in substitute production. While closure is not predicted for any of these companies, it cannot be ruled out. The shutdown of styrene derivative facilities would have substantial effects on several firms.

There are a number of firms which produce styrene derivatives but not styrene monomer. If styrene monomer is not forthcoming from foreign sources, derivative plants would close. While some derivative producers are large, diversified companies, some are vertically integrated firms which take the styrene derivative forward toward the final good market. Such firms face potential impacts which are larger than sales percentages would indicate.

7.4.4.2 Indirect Impacts

The indirect impacts of a ban on domestic styrene production would be felt primarily by feedstock suppliers and fabricators who purchase styrene derivatives for the production of final goods. In particular, three firms who produce ethylbenzene from mixed xylenes for merchant sale only would be affected. Total production for these firms is greater than the demand for EB for solvent purposes, which constitutes the only use of EB for other than styrene production. It is possible that one or more of these plants would not continue to operate. However, since each plant is owned by a petroleum refinery and is based on mixed xylenes for which there are alternative markets, firm closure is not anticipated.

Raw materials for EB/S production are primarily benzene and ethylene. EB production consumes approximately 50 percent of the benzene produced in the United States. Demand for benzene is currently quite high. Export potential is considerable at the moment. Should foreign producers wish to expand styrene capacity in order to supply the U.S. market, they would need additional feedstocks for some time. But note that should benzene be shipped elsewhere for styrene production and styrene or a derivative be shipped back, costs and prices could increase considerably. In some uses, styrene would no longer be able to compete with substitutes. Some impact on benzene producers would be unavoidable.

Some effect may be felt in the ethylene market also. In 1978, ethylene consumption in EB/S production was less than ten percent of domestic ethylene capacity. However, unlike the benzene market, the ethylene market currently suffers from a slight lack of demand. This slack makes the industry more vulnerable to any further decrease in demand. Ethylene is produced by approximately 25 companies of varying sizes and degrees of diversification. Producers are geographically concentrated in Texas and Louisiana as would be any diverse impacts from the industry.

A large number of firms purchase styrene derivatives for the production of final goods. Such firms possess varying abilities to switch production materials. In all cases there are retooling and retraining costs associated with switching from one resin to another. In some cases those costs would be prohibitive. For firms which specialize in making one specific product for a regional market, the result would be closure if they could not import enough of their basic inputs. Such inputs would be difficult to secure in the near future.

7.4.4.3 Substitutes for Styrene

Styrene derivatives are used in the production of a variety of final goods (see Table 7-27). Should domestic styrene production be banned and the derivative chemicals be unavailable through import, fabricators would need to find substitutes for the styrene chemicals. Generally, a chemical is chosen for use for a variety of mechanical, optical, electrical, chemical, and other properties. Where clarity is of predominant importance, acrylates and polycarbonates can be used in place of styrene. If impact resistance is required, polyolefins, nylons, or acetals may be substituted. There are other materials which are compatible with a variety of fillers and pigments.

TABLE 7-27. POSSIBLE STYRENE SUBSTITUTES[17,50,51,52,53]

Styrene End Use	1974 Styrene Consumption 10^3 Mg (% of Total)	Possible Substitute
Packaging	499 (22)	Polyethylene, Polypropylene, Polyvinyl Chloride, Paper
Construction-Related Markets	360 (16)	
Construction	119	Polyvinyl Chloride, Polyurethane, Mineral Wool
Pipe	115	Polyvinyl Chloride, Chlorinated Polyvinyl Chloride
Industrial Rubber Products	80	Natural Rubber, Polybutadiene, Ethylene Propylene Rubber
Lighting Fixtures, Signs	23	Polycarbonate
Paint	10	Polyvinyl Alcohol, Polyvinyl Chloride, Acrylics
Corrosion-Resistant Goods	12	Polypropylene, Polyvinyl Chloride
Electrical Appliance, TV, Communication, and Office Machine Markets	282 (12)	
Appliance and TV	154	Nylon, Acetal, Phenols, Polyvinyl Chloride, Aluminum, Polycarbonates
Electrical and Other	128	
Household Goods	266 (12)	
Housewares, Furnishings	129	Phenolics, Urea-formaldehyde
Carpeting and Flooring	68	Polyvinyl Alcohol, Polyvinyl Chloride, Polyvinyl Acetate
Furniture	54	Wood, Polyvinyl Chloride, Cellulosics
Synthetic Marble	15	Unknown
Transportation-Related Markets	219 (10)	
Tires	143	Natural Rubber, Polybutadiene
Auto, Truck, Bus Parts	64	Nylon, Acetal, Metals
Auto Putty	8	Epoxy
Miscellaneous Transportation	4	Unknown
Recreation-Related Markets	186 (8)	
Toys, Sporting Goods	147	Polyethylene, Polypropylene, Polyvinyl Chloride
Marine	24	
Recreational Vehicles	15	Nylon, Acetal, Phenolics
Disposable Serviceware	104 (5)	Paper Plates, Polypropylene
Miscellaneous	246 (11)	
1) Industrial Products	108	
Paper Coatings, Additives	58	Polyvinyl Alcohol, Polyvinyl Chloride
Ion Exchange Resins	22	Zeolites, Activated Carbon, Membrane Materials
Medical, Dental Lab Equipment	23	Unknown
Impact Modifiers		Unknown
2) Consumer Products	97	
Novelties	43	Unknown
Writing Utensils	24	Unknown
Personal Care Items	23	Polypropylene
Luggage and Cases	5	Unknown
Floor Polishes		Acrylics
3) Other	41	Unknown
Exports	110 (5)	Unknown
Total	2,272 (100)	

However, where a combination of properties is required, potential substitutes, if they exist at all, can be expected to result in a final product which is only similar to the original one. The degree of similarity will vary from case to case. In addition, many final goods will be more expensive when produced with substitute chemicals.

One potential problem area is the production of synthetic rubber. Styrene-butadiene rubber (SBR) has become almost indispensible in the tire rubber market. While both natural rubber and a variety of synthetic rubber materials exist, many rubber products such as tires are made from a combination of materials. Such products made without SBR might be in some sense inferior. In addition, there is the question of the availability of substitutes for SBR. More natural rubber cannot be had immediately. Production of the other synthetics can be increased only with time.

The question of availability applies to all potential substitutes. Polypropylene is expected to remain fairly plentiful through 1983 and beyond.* However, both low and high density polyethylene are expected to be in tight supply through 1983. Demand for polyvinyl chloride is increasing and a general shortage currently is predicted for 1983. There is extreme tightness in the phenol market currently, but that tightness is partially due to plant problems. Markets for polyvinyl alcohol, acetals, polybutadiene, and various cellulose resins are characterized by small numbers of producers with fairly small capacities.

It is likely that substitute chemicals for a variety of uses would not be available in sufficient quantities to fill the void left by styrene for several years and in some cases longer. The magnitude of capital requirements and the length of construction lead times will limit the availability of domestically produced styrene substitutes and imports of styrene and its substitutes.

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*Not including any demand increase as a result of a styrene production ban.

It also must be noted that increased production of substitute chemicals can have environmental and health impacts similar to those of styrene production. In particular, the various processes which result in polyvinyl chloride can produce vinyl chloride emission. Vinyl chloride is also a carcinogen.

7.4.4.4 Summary

Complete prohibition of benzene emissions in styrene production would require closure of styrene production because no existing technology will achieve a zero emission limitation. Banning production of styrene would have a substantial negative impact on the producing companies. The magnitude of that impact would depend upon whether the production of styrene derivatives also must be discontinued. If derivative chemicals are no longer available, small specialized fabricators who further process such chemicals may face closure. Whatever happens to derivative production, feedstock producers also will experience negative impacts. Overall, considerable loss of capital investment could be expected.

Employment impacts would depend upon the future of derivatives production. Styrene monomer production directly involves fewer than 1,000 employees. Derivative chemical production may involve more than 10,000 employees. Regardless of the future of derivatives production, output, employment, and income, impacts will be concentrated geographically to some degree in Texas and Louisiana. A multiplier impact can be anticipated in some areas.

It is unlikely that foreign styrene production would be sufficient to maintain current levels of domestic consumption of final goods based on styrene. Goods which continue to be produced with styrene would be more expensive for a variety of reasons (e.g., transportation costs).

There are substitutes for styrene in some but not all applications. Some products may cease to exist under substitution. Where substitutes exist, they do not necessarily have all of the desirable properties of the styrene chemical replaced. The consumer goods produced through substitutes may be in some sense inferior, as well as more expensive. For a variety of substitutes, availability would present a potential problem in the short term. Limited capacities for substitute chemicals likely would result in price increases under increased substitute demand. This would render consumer goods even more expensive.

7.5 POTENTIAL SOCIOECONOMIC AND INFLATIONARY IMPACTS

The socioeconomic impacts of the 85 percent, the 94 percent, and the 99 percent regulatory options are not expected to be large. These impacts can be summarized as follows:

(i) Annualized Costs. Total annualized costs in the fifth year following promulgation are estimated to be -\$0.608 million, -\$0.202 million, and -\$0.460 million for the 85, 94, and 99 percent options, respectively. Note that these estimates are based on existing plants. Any new construction planned or started between now and promulgation would face control requirements also. However, total annualized costs including any such new plants would not surpass the critical level of \$100 million.

(ii) Price Impacts (Inflation). The maximum estimated price increase required to maintain a 15 percent rate of return which could be passed on is \$2.14/Mg, or 0.46 percent of product price. Potential price increases are, therefore, well below the five percent requirement for regulatory analysis.

(iii) Employment Impacts. Impacts on employment are expected to be negligible. Labor time required to operate and maintain controls and monitors may be greater than labor displaced by potential demand decreases (due to price increases).

(iv) Demand for Critical Materials. The only critical materials likely to be affected by the proposed controls for benzene emissions in the EB/S industry are plastics. If demand for styrene (a plastic material) decreases, the demand for other plastic materials will increase. Such impacts are expected to be small. Moreover, they involve the substitution of one plastic material for another. This does not constitute necessarily an increase in the demand for plastics overall.

The potential socioeconomic impacts of the 100 percent regulatory option (closure) are much larger. Impacts would be concentrated geographically. Income and employment effects in Texas and Louisiana could be substantial. The degree of impact would depend upon whether or not plants producing styrene derivatives could continue to operate by importing styrene. If they could not, employment and income impacts would be substantial. Some businesses could be expected to close under these circumstances. Shortages of good substitutes for styrene chemicals also could be expected.

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APPENDICES

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD

Date	Company, Consultant, or Agency	Nature of Action	Location
9/72	EB/S Plants	Responses to Houdry questionnaires	U.S.
7/76	EB/S Manufacturing Companies	EIQ's to Texas Air Control Board	Texas
6/16/77	Cos-Mar	Plant visit	Carville, LA
7/28/77	Cos-Mar	Plant visit	Carville, LA
7/29/77	Dow Chemical	Plant visit	Freeport, TX
9/8/77	Dow Chemical	Plant visit	Freeport, TX
9/20/77	Dow Chemical	Discussion of process	Durham, NC
12/14/77	El Paso Natural Gas, Co.	114 Request for Information	Durham, NC
12/14/77	Gulf Science & Technology, Company	114 Request for Information	Durham, NC
12/21/77	Monsanto Chemical Intermediates Company	114 Request for Information	Durham, NC
12/22/77	American Hoechst	114 Request for Information	Durham, NC
12/22/77	Atlantic Richfield Co.	114 Request for Information	Durham, NC
1/26/78	American Hoechst Corp.	Response to 114 letter	Baton Rouge, LA
1/31/78	El Paso Products Co.	Response to 114 letter	Odessa, TX
1/31/78	Gulf Oil Chemicals Co.	Response to 114 letter	St. James, LA

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD (Continued)

Date	Company, Consultant, or Agency	Nature of Action	Location
2/23/78	Atlantic Richfield Co.	Response to 114 letter	Port Arthur, TX
4/28/78	Monsanto Chemical Intermediates Co.	Response to 114 letter	Texas City, TX
5/25/78	Hydroscience	EB/S Product Report	Knoxville, TN
6/26/78	Cos-Mar	Emission Test	Carville, LA
8/7/78	Amoco Chemicals Corp.	114 Request for Information	Durham, NC
8/7/78	Gulf Oil Chemicals	114 Request for Information	Durham, NC
8/17/78	Gulf Oil Chemicals Co.	Discussion of Process	St. James, LA
9/14/78	Dow Chemicals Corp.	114 Request for Information	Durham, NC
10/11/78	Sun Petroleum Products	114 Request for Information	Durham, NC
10/18/78	American Hoechst	114 Request for Information	Durham, NC
10/18/78	Oxirane Corp.	Plant visit	Channelview, TX
10/24/78	Dow Chemicals USA	114 Request for Information	Durham, NC
10/26/78	Oxirane Corp.	114 Request for Information	Durham, NC
11/2/78	Gulf Oil Chemicals Co.	Discussion of Process	St. James, LA
11/7/78	Sun Petroleum Products	Response to 114 letter	Corpus Christi, TX
11/9/78	Oxirane Corp.	Response to 114 letter	Channelview, TX

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD (Continued)

Date	Company, Consultant, or Agency	Nature of Action	Location
1/25/79	U.S. Steel Corp.	Response to 114 letter	Houston, TX
1/30/79	Corning Glass Works	Packed tower discussion	Durham, NC
2/6/79	Process Combustion Corp.	Information on EB/S offgas burner	
2/12/79	Chem-Pro Equipment	Discussion of benzene absorption tower costs	
2/21/79	Sundstrand Fluid Handling	Endorsement of EPA centrifugal compressor data	
2/24/79	Amoco	Pretest survey	Texas City, TX
3/15/79	Dow Chemical	Plant visit	Midland, MI
3/21/79	Sun Petroleum Products	114 Request for Information	Durham, NC
3/30/79	American Hoechst	114 Request for Information	Durham, NC
3/30/79	Atlantic Richfield Co.	114 Request for Information	Durham, NC
3/30/79	Gulf Oil and Refining	114 Request for Information	Durham, NC
3/30/79	Monsanto Research Corp.	114 Request for Information	Durham, NC
4/30/79	Amoco Chemicals Corp.	114 Request for Information	Durham, NC
4/30/79	El Paso Natural Gas	114 Request for Information	Durham, NC
4/30/79	Monsanto Chemical Intermediates Co.	Request for plant visit	Durham, NC
5/7/79	Amoco	Emission test	Texas City, TX

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD (Continued)

Date	Company, Consultant, or Agency	Nature of Action	Location
11/2/78	Gulf Oil Chemicals Co.	Discussion of process	St. James, LA
11/7/78	Sun Petroleum Products, Co.	Response to 114 letter	Corpus Christi, TX
11/9/78	Oxirane Corp.	Response to 114 letter	Channelview, TX
11/29/78	Atlantic Richfield Corp.	114 Request for Information	Durham, NC
11/30/78	Dow Chemical USA	Response to 114 letter	Texas
12/1/78	Cosden Oil and Chemical Co.	114 Request for Information	Durham, NC
12/5/78	Cosden Oil and Chemical Co.	Information that Cosden styrene unit closed	Big Spring, TX
12/13/78	Ingersoll-Rand	Request information on compressor costs	Durham, NC
12/13/78	Sundstrand Fluid Handling	Request information on compressor costs	Durham, NC
12/15/78	Dow Chemical USA	Response to 114 letter	Midland, MI
1/15/79	Gulf Oil Chemicals Co.	Discussion of process	St. James, LA
1/19/79	Cos-Mar	Vent condenser discussion	Durham, NC
1/19/79	EEA	Request for information concerning American Hoechst's scrubber and surface condenser	Durham, NC
1/24/79	Bloom Engineering	Low pressure burner cost request	Durham, NC

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD (Continued)

Date	Company, Consultant, or Agency	Nature of Action	Location
5/14/79	Monsanto Chemical Intermediates Co.	Plant visit	Texas City, TX
5/22/79	Cosden Oil	114 Request for Information	Durham, NC
5/23/79	Amoco Chemicals Corp.	Response to 114 letter	Texas City, TX
5/29/79	Monsanto Chemical Intermediates Co.	Response to 114 letter	Texas City, TX
6/20/79	Monsanto Chemical Intermediates Co.	Emission Test Request	Durham, NC
6/28/79	El Paso Products Co.	Response to 114 letter	Odessa, TX
7/12/79	EEA	Draft EB/S BID	Durham, NC
7/20/79	Gulf Oil Chemicals Co.	Discussion of process	St. James, LA
7/25/79	Monsanto Chemical Intermediates Co.	Pretest survey	Texas City, TX
9/19/79	EEA, RTI	EB/S Draft BID, Regulation	Durham, NC
8/3/79	El Paso Products Co.	Emission Test Request	Durham, NC
8/3/79	U.S. Steel	Emission Test Request	Durham, NC
10/1/79	El Paso Products Co.	Emission Test	Odessa, TX
10/12/79	Oxirane Corp.	Response to Request for Information	Houston, TX
10/26/79	Oxirane Corp.	114 Request for Information	Durham, NC

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD (Continued)

Date	Company, Consultant, or Agency	Nature of Action	Location
11/15/79	EPA	Working Group Meeting on benzene standard for EB/S	Durham, NC
11/19/79	Oxirane Corp.	Response to 114 letter	Houston, TX
12/7/79	Amoco Chemicals Corp.	Request for retest of EB/S Facility in Texas City, TX	Durham, NC
12/12/79	EPA	NAPCTAC meeting on benzene standard for EB/S	Durham, NC
1/9/80	Monsanto Chemical Intermediates Co.	114 Request for Information	Durham, NC
1/9/80	Dow Chemical U.S.A.	114 Request for Information	Durham, NC
1/9/80	Oxirane Corp.	114 Request for Information	Durham, NC
1/9/80	Cosden Oil and Chemical Co.	114 Request for Information	Durham, NC
1/16/80	Beveridge, Fairbanks, and Diamond	Freedom of Information Request	Washington, DC
2/21/80	Oxirane Corp.	Comments on NAPCTAC Package	Houston, TX
2/22/80	Dow Chemical U.S.A.	Comments on NAPCTAC Package	Midland, MI
3/10/80	Cosden Oil and Chemical Co.	Comments on NAPCTAC Package	Big Spring, TX
4/25/80	Monsanto Chemical Intermediates Co.	Response to 114 letter	St. Louis, MO.

APPENDIX A -- EVOLUTION OF THE PROPOSED STANDARD (Continued)

Date	Company, Consultant, or Agency	Nature of Action	Location
5/2/80	EPA	Steering Committee Meeting on benzene standard for EB/S	Washington, DC
5/2/80	EPA	Interagency Regulatory Liaison Group's benzene task group meeting on benzene standard for EB/S	Washington, DC

APPENDIX B

ENVIRONMENTAL IMPACT CONSIDERATIONS

B.1 CROSS-INDEXED REFERENCE SYSTEM TO HIGHLIGHT ENVIRONMENTAL IMPACT PORTIONS OF THE DOCUMENT

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document (BID)
1. Background and summary of Regulatory Alternatives.	The regulatory alternatives from which standards will be chosen for proposal are summarized in Chapter 5, page 5-7 and in the Addendum to the BID on Excess Emissions, pages 3-7 through 3-9.
The relationship to other regulatory agency actions.	Other EPA regulations and, to the extent possible, the OSHA regulations that apply to the affected industries are included in the study of economic impact in Chapter 7, pages 7-45 through 7-51.
Industry affected by the regulatory alternatives.	The industry and the emission sources within the industry affected by the regulatory alternatives are listed in Chapter 3, pages 3-1 through 3-28.
Specific processes affected by the regulatory alternatives.	The specific processes and facilities affected by the regulatory alternatives are summarized in Chapter 1, Section 1.1, page 1-1. A detailed technical discussion of the sources and processes affected by the regulatory alternatives is presented in Chapter 3, Section 3.3, pages 3-6 through 3-22.
Applicable control technologies.	The control technologies which can be applied to reduce benzene emissions in the ethylbenzene/styrene plants and the emission reductions which have been achieved by these control technologies are described in detail in Chapter 4, pages 4-1 through 4-10.
Applicable enforcement approaches.	The applicable enforcement approaches include 1) enforcement procedures which are discussed in the Addendum to the BID, and 2) applicable formats for the test method which are described in Appendix D, pages D-3 through D-4.

B.1 CROSS-INDEXED REFERENCE SYSTEM TO HIGHLIGHT ENVIRONMENTAL IMPACT PORTIONS OF THE DOCUMENT (Continued)

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document (BID)
2. Agency's comparative evaluation of the beneficial and adverse environmental effects of each reasonable alternative.	a. A discussion of the Agency's comparative evaluation of the various alternative regulatory options for benzene emissions can be found in Chapter 5, Sections 5.2 and 5.3, pages 5-4 through 5-7. b. A detailed description of the environmental impacts of each regulatory option can be found in Chapter 6, pages 6-1 through 6-16. A detailed description of the economic impacts of each regulatory option, including the capital and annualized costs to the industry, can be found in Chapter 7, Section 7.1 and 7.2, pages 7-1 through 7-44. The socioeconomic impacts of the regulatory options, including potential plant closures and maximum price increases in consumer products, also can be found in Chapter 7, Section 7.4, pages 7-52 through 7-84. c. The Agency's comparative evaluation of the alternative enforcement approaches are in Appendix D, pages D-1 through D-8.
3. Environmental impact of the regulatory options.	
a. Primary impact Primary impacts are those that can be attributed directly to an action, such as reduced levels of specific pollutants brought about by a new standard and the physical changes that occur in the various media with this reduction.	Air impact modeling shows the primary impacts for each regulatory option in terms of model plants and for individual emission sources in Chapter 6, Section 6.1.1, pages 6-6 through 6-8. Effects of each option on nationwide emissions are discussed in Section 6.1.2, pages 6-8 through 6-10.

B.1 CROSS-INDEXED REFERENCE SYSTEM TO HIGHLIGHT ENVIRONMENTAL IMPACT PORTIONS OF THE DOCUMENT (Continued)

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document (BID)
b. Secondary impact	
Secondary impacts are indirect or induced impacts. For example, mandatory reduction of specific pollutants brought about by a new standard could result in the adoption of control technology that exacerbates another pollution problem and would be a secondary impact.	Other environmental impacts of each regulatory option are identified qualitatively in Chapter 6, Sections 6.3 and 6.4, pages 6-10 through 6-14. The secondary water impacts of the regulatory options are quantified in Chapter 6, Section 6.3, page 6-10. The energy consumption impact of the regulatory options is quantified in Chapter 6, Section 6.5, pages 6-14 through 6-16.
4. Other considerations.	
a. Adverse impacts which cannot be avoided should the regulatory options be implemented.	A discussion of the potential adverse environmental impacts of the regulatory options and a discussion of the significance of each impact can be found in Chapter 1, Section 1.2 and Chapter 6 Sections 6.2 through 6.7. Factors which already exist to eliminate some of the potential adverse impacts are identified. Those adverse impacts which cannot be avoided also are identified, along with any steps which can be taken to minimize them.
b. Irreversible and irretrievable commitments of resources which would be involved in each regulatory option should it be implemented.	Irreversible and irretrievable resources which would be involved in each regulatory option are discussed in Chapter 6, Section 6.6.

B.2 GENERAL MODELING METHODOLOGY

The ISC model consists of two separate models: a short-term model (ISCST), which normally is used for averaging periods of from one to 24 hours and a long-term model (ISCLT), which is used to predict seasonal or annual average concentrations. In this study, the short-term model was used to calculate one-hour, eight-hour, and 24-hour average concentrations; the long-term program was used to predict annual averages.

Both the short-term and the long-term models use Gaussian plume dispersion equations and Pasquill-Gifford dispersion coefficients. For the model features used in this study, the ISCST program corresponds to the Single Source (CRSTER) Model, modified to include the effects of the separation of individual sources and the effects of area source emissions.[1] The ISCLT program, which is a sector-averaging model similar to the Air Quality Display Model (AQDM) or the Climatological Dispersion Model (CDM), makes the same basic model assumptions as the ISCST program.[2,3] However, the ISCLT program uses Statistical Array (STAR) summaries (statistical tabulation of the joint frequency of occurrence of wind-speed and wind-direction categories, classified according to the Pasquill stability categories) to calculate annual average concentrations. For the same source data and meteorological data base, ISCLT calculates annual average concentrations that are equivalent to those obtained from ISCST using a year of sequential hourly meteorological data.

The source characteristics required by the ISC model are stack height and diameter, stack gas temperature, and exit velocity. These parameters are given for all sources of the model plant in Tables B-1 and B-2,

TABLE B-1. STACK SOURCE CHARACTERISTICS

Regulatory Option	Source	Emission Rate[a] (G per sec)	Height (meters)	Temp. (Deg.K)	Exit Vel. (m/sec)	Diameter (meters)
Uncontrolled[b]	Atmospheric Pressure Columns	6.30 (5.94)	12.00	318.00	0.10	0.33
		6.30 (5.94)	12.00	318.00	0.10	0.33
	Alkylation Reaction Vents	1.60 (1.51)	12.00	318.00	4.90	0.06
		1.60 (1.51)	12.00	318.00	4.90	0.06
	Benzene/Toluene Column	3.10 (2.92)	12.00	318.00	0.10	0.23
	Vacuum Columns	0.20 (1.90)	12.00	318.00	0.10	0.11
		0.20 (1.90)	12.00	318.00	0.10	0.11
		0.20 (1.90)	12.00	318.00	0.10	0.11
Condenser/ Absorber (C/A)	All above process streams	1.90 (1.79)	12.00	283.00	4.70	0.06
		0.47 (0.44)	12.00	283.00	9.80	0.06
		0.53 (0.50)	6.00	283.00	2.00	0.06
C/A and 3" Flare[c]	All above process streams	1.14 (1.07)	29.00	823.00	0.10	3.30
Boiler	All above process streams	0.10 (0.09)	30.00	473.00	6.20	2.00
	H_2 Separation Section	0.44 (0.41)	30.00	473.00	6.20	2.00
Flare[c]	H_2 Separation Section	44.44 (0.06)	90.00	823.00	0.10	13.70
Uncontrolled	H_2 Separation Section	111.11 (0.14)	6.00	318.00	19.80	0.50

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[a] First emission rate is maximum hourly rate in grams per second, with annual average rate in grams per second in parentheses.

[b] The atmospheric pressure columns discharge horizontally and the benzene/toluene and vacuum columns discharge downward. Values given are the modeling inputs for these sources, after adjustments as discussed in the text. The actual stack height and diameter for these sources are 12.0 and 0.06 m, respectively.

[c] Values given are the modeling inputs for the flares, after adjustments as discussed in the text. Actual characteristics for the flares are:
3-inch flare: height = 20m, diameter = 0.1m, flow rate = $0_3 05m^3$/sec.
H_2 flare: height = 60m, diameter = 0.3m, flow rate = 3.89m^3/sec.

TABLE B-2. STORAGE TANK AND FUGITIVE SOURCE CHARACTERISTICS

Source	Emission Rate ($g/(sec-m^2)$)	Source Height (meters)	Source Width (meters)
Area Source 1	0.00014	3.0	40.0
Area Source 2	0.00014	3.0	40.0
Small Benzene Tank[a]	6.69	12.2	0.5
Benzene/Toluene Tank[a]	1.27	9.1	0.5
Large Benzene Tank	0.00023	12.2	31.0

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[a] The small benzene and benzene/toluene tank vent through a 0.5m pipe capped by an annular ring.

according to each regulatory option. Fugitive and storage emissions are assumed to be uncontrolled throughout each regulatory option.

Since the ISC model is designed for upward-venting stacks, the characteristics of some sources were modified to provide suitable input to the model. Sources requiring modification are the flares and some of the uncontrolled process vents which discharge downward or horizontally.*

For the flare, it was assumed that the combustion gas plume begins at the top of the flame at a temperature of 550°C with very little upward momentum (i.e., a negligible exit velocity). The volume flow rate for the flare combustion gas was calculated based on the characteristics and flow rate of the fuel. The stack diameter was set to correspond to the volume flow and the assumed exit velocity (0.1 meters per second (m/sec)).** Thus, for the modeling, the flare plume was simulated by a stack plume having a height of emissions equal to the height of the flame above the ground; the stack diameter, gas temperature, and gas exit velocity were set as described.

For the process sources venting downward or horizontally, the exit velocity was lowered to 0.1 m/sec and the stack diameter correspondingly increased to maintain the same gas flow rate in the model.+ Because of the

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[*] Downward (vacuum column vents) and horizontally (atmospheric pressure/column vents) discharging sources appeared only on the uncontrolled plant.

[**] This is based on the relationship that cross-sectional stack area (which is related to diameter) multiplied by exit velocity equals volume flow. The hypothetical stack diameters calculated in this fashion were close to the actual diameter of the flame at flame height.

[+] This causes the model to calculate plume rise solely on the basis of gas buoyancy, since upward momentum of these plumes is assumed to be negligible after downward plume jet momentum is expended. It was determined that because of the low exit velocity of the downward venting plumes (0.3 to 1.5 m/sec), momentum would carry the plume only a negligible distance downward before buoyancy predominated.

approximate nature of these adjustments, the impacts predicted for the flare and the downward or horizontally venting process sources may be less accurate than predictions for other sources. However, they will still be suitable for this analysis since all adjustments would tend to err conservatively.

Houston was chosen as the location of the model plant because almost all EB/S plants are in the Gulf Coast region of Texas and Louisiana and more than half are within 200 miles (320 kilometers (km)) of Houston. Meteorological data for the modeling were obtained from Houston's Hobby Airport, which is ten miles (16 km) from the center of the city.[4] Since the model plant is assumed to be in a moderately developed area, ISC's urban dispersion coefficients (mode one) were used (this is a conservative assumption).

ISCST requires hourly surface meteorological data (e.g., wind speed and direction, stability class, and temperature) and twice-daily mixing height data for each day it is run. Hourly surface data (1964) for Hobby Airport and mixing height data (1964) for Lake Charles, Louisiana[5] were used in the short-term modeling.[*] The principal meteorological information used in ISCLT is the stability wind-rose (STAR) summary for Hobby Airport compiled for the period 1964 to 1968.[6]

The ISC Model contains numerous options and features that may be used to simulate dispersion of emissions from the wide variety of sources found in an industrial source complex. Because of the requisite complexity of the ISC Model, it usually is unfeasible economically to use the ISCST program to calculate hourly concentrations for a year of sequential hourly meteorological data, the procedure generally followed with the Single Source (CRSTER) Model. However, from a knowledge of the critical meteorological conditions affecting emissions from EB/S plants, it was possible to select 12 24-hour periods representative of worst-case dispersion conditions. ISCST then was executed only for those days to obtain maximum one-hour, eight-hour, and 24-hour average benzene concentrations.

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[*] Lake Charles is 135 miles from Houston. However, mixing height can be estimated with reasonable accuracy from stations up to 180 miles away because vertical temperature profiles above about 200 meters are governed by synoptic scale meteorological phenomena. Mahoney, James R. Meteorological Aspects of Air Pollution. In: Industrial Pollution, ed. by N. Irving Sax. New York, Van Nostrand Reinhold Co., 1974.

The worst-case meteorological conditions were selected as follows. First, the ratio of the vector mean wind speed to the scalar mean wind speed was computed for each day of 1964 from the Hobby Airport hourly surface observations. This ratio has a value near unity for days of persistent wind directions. The days with ratio values near unity then were examined to select days with stable conditions and light-to-moderate persistent winds. Based on analysis of the source characteristics and test runs using the PTMAX dispersion model,[7] these were considered to be worst-case meteorological conditions for the small process sources (i.e., uncontrolled vents and condenser/absorption tower) and the fugitive and storage sources. However, some days also were selected with unstable conditions and light-to-moderate winds since these were shown on test runs to provide worst-case conditions for the flares and boiler.

The objective of the dispersion modeling is to estimate maximum benzene concentrations at any distance and at 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 10.0, and 20.0 km from the plant. Therefore, receptors first were placed at these distances along 30 radial axes originating at a reference point in the model plant complex (shown in Figure 6-1).

Maximum concentrations produced by fugitive and storage tank emissions can be expected to occur in the immediate vicinity of the plant production area. However, the dispersion coefficients used by the ISC Model (the Pasquill-Gifford curves) do not apply at a downwind distance less than 100 m from the source. Therefore, a ring of receptors was placed at 0.16 km which is the smallest practical placement that would maintain a distance of at least 100 m between receptors and sources and still capture the maximum impacts of fugitive and storage emissions (See Table B-3).

Test runs were made using ISCST and PTMAX to predict the distance to maximum concentration for each of the stack sources. These showed that the ring distances mentioned above were sufficient to determine maximum short-term concentrations and that an additional receptor ring at 5 km was necessary for the long-term model runs.

TABLE B-3. AMBIENT BENZENE IMPACTS FROM INDIVIDUAL AND GROUP SOURCES
(concentrations in ug/m^3)

Source or Source Group		0.16 km	0.3 km	0.5 km	0.7 km	1.0 km	1.5 km	2.0 km	5.0 km	10.0 km	20.0 km
Process Emissions -- Uncontrolled	1	7472	11317	6783	4402	2560	1394	899		108	59
	8	2579	2777	1532	912	502	310	235		54	28
	24	999	1350	593	333	205	113	78		18	9
	Annual Average	338	296	150	88	48	26	16	4	1	0.4
Process Emissions -- Condenser/Absorption Tower	1	1470	1781	1059	675	389	211	135		16	9
	8	511	438	236	139	77	47	36		8	4
	24	190	218	90	53	31	17	12		3	1
	Annual Average	65	46	23	13	7	4	2	1	0.2	0.1
Process Emissions -- Condenser/Absorption Tower/Flare	1	40	45	29	32	33	29	24		5	3
	8	8	12	17	22	21	16	13		3	1
	24	3	4	6	7	7	5	4		1	0.1
	Annual Average	0.2	1	2	2	2	1	1	0.2	0.1	N
Process Emissions -- Boiler	1	0.2	0.5	1	1	1	0.4	0.3		0.1	0.1
	8	N	0.1	0.1	0.2	0.2	0.2	0.2		N	N
	24	N	N	0.1	0.1	0.1	0.1	0.1		N	N
	Annual Average	N	N	0.03	0.04	0.04	0.03	0.03	N	N	N
Fugitive Sources	1	1016	501	218	130	72	39	25		3	2
	8	263	130	52	28	15	9	7		1	1
	24	121	48	17	10	6	3	2		0.5	0.3
	Annual Average	27	10	4	2	1	1	0.4	0.1	N	N
Storage Tanks	1	1291	1241	763	449	256	142	94		12	6
	8	326	393	223	128	72	43	32		6	3
	24	178	143	74	43	24	14	10		2	1
	Annual Average	38	24	13	8	4	2	2	0.4	0.1	N
Hydrogen Separation Section -- To Boiler	1	1	2	3	2	2	2	1		1	0.3
	8	0.1	0.3	1	1	1	1	1		0.1	0.1
	24	0.3	0.1	0.2	0.4	1	1	0.4		0.1	N
	Annual Average	N	N	0.2	0.3	0.3	0.2	0.2	0.1	N	N
Hydrogen Separation Section -- To Flare Annual Emission Rate	1	N	N	0.2	0.2	0.1	0.1	0.1		N	N
	8	N	N	N	N	N	N	N		N	N
	24	N	N	N	N	N	N	N		N	N
	Annual Average	N	N	N	N	N	N	N	N	N	N
Hydrogen Separation Section -- To Flare Maximum Emission Rate	1	0.1	20	124	137	99	81	69		28	20
	8	N	3	16	32	22	19	14		7	5
	24	N	1	5	6	7	6	7		4	2
Hydrogen Separation Section -- Uncontrolled Annual Emission Rate	1	25	20	16	14	11	8	5		1	0.4
	8	14	10	7	4	3	2	2		0.4	0.2
	24	7	6	3	2	1	1	1		0.1	0.1
	Annual Average	1	1	1	1	0.3	0.2	0.1	N	N	N
Hydrogen Separation Section -- Uncontrolled Maximum Emission Rate	1	20373	16032	12526	10909	9035	6002	4240		651	352
	8	10949	7974	5234	3079	2378	1716	1349		321	169
	24	5693	5077	2541	1609	1043	600	450		107	56
Uncontrolled Model Plant	1	7590	12305	7350	4845	2856	1573	1018		123	67
	8	3060	3127	1754	1052	581	362	274		62	32
	24	1247	1541	681	378	226	126	91		21	11
	Annual Average	400	330	167	98	54	29	18	4	1.4	1
Plant with Condenser/ Absorption Tower	1	2410	3103	1795	1164	605	389	255		31	17
	8	992	786	458	279	161	99	74		16	8
	24	423	409	177	95	54	33	25		5	3
	Annual Average	127	79	39	23	13	7	5	1	0.4	0.1
Plant with Condenser/ Absorption Tower/Flare	1	1846	1423	912	583	352	206	140		20	11
	8	452	491	285	177	109	68	51		10	5
	24	262	191	95	59	36	22.8	16.9		3	2
	Annual Average	63	35	19	12	7	4	3	1	0.2	0.1
Plant with Boiler	1	1846	1423	906	562	322	178	119		15	8
	8	481	486	268	155	87	52	38		8	4
	24	262	191	89	52	29	17	13		1	1
	Annual Average	63	34	17	10	6	3	2	1	0.2	0.1

N = negligible, i.e., <0.05 µg/m^3

B.3 REFERENCES FOR APPENDIX B

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4. Airways Surface Observations (TD-1440) for Station 12918, Houston/Hobby, Texas, 1964. National Climatic Center. Asheville, North Carolina.

5. Mixing Heights for Station 03937, Lake Charles, Louisiana, 1964. National Climatic Center. Asheville, North Carolina.

6. STAR Normalized Data (TD-9773) -- Annual for Station 12918, Houston/Hobby, Texas, 1964. National Climatic Center. Asheville, North Carolina.

7. Turner, B. and A. Burse. EPA, National Environmental Research Center. User's Guides to PTMAX, PTDIS, and PTMTP. Research Triangle Park, North Carolina. June 1973.

APPENDIX C

EMISSION SOURCE TEST DATA

C.1 INTRODUCTION

The purpose of this appendix is to present and summarize data gathered during the development of a standard for benzene emissions from the production of ethylbenzene/styrene. The facilities tested are described and the source testing methods are identified. Any reference to commercial products and processes by name does not constitute endorsement by the U.S. Environmental Protection Agency.

C.2 SUMMARY

Three facilities producing ethylbenzene/styrene were tested to determine percent reduction and exit concentrations of benzene. Samples were analyzed for:

- CO_2, O_2, N_2, H_2, CH_4, by GC/TC.
- Benzene, toluene, xylene, ethylbenzene, styrene by GC/FID.
- Low molecular weight hydrocarbons (C_1-C_6) by GC/FID.
- Total hydrocarbons as benzene by FID.
- Moisture content by EPA standard method.

C.3 DESCRIPTION OF FACILITIES AND TEST PROCEDURES

Ethylbenzene for styrene production is made by (1) benzene alkylation with ethylene and (2) extraction from mixed xylene streams. Styrene is produced from ethylbenzene predominantly by ethylbenzene dehydrogenation. The three EB/S facilities tested use benzene alkylation to produce ethylbenzene, followed by ethylbenzene dehydrogenation to produce styrene. The basic process description for this manufacturing scheme is presented in Chapter 3.

The following sections briefly describe some process details for each plant and summarize the test procedure followed.

C.3.1 Plant A[1]

This plant consists of two separate trains of equipment to produce styrene. The total published capacity for the plant is 590 x 10^3 Mg/yr styrene from 689 x 10^3 Mg/yr ethylbenzene. The emission test was conducted on one train with a styrene capacity of 318 x 10^3 Mg/yr. At all times during the test, the unit was running between 90 and 100 percent of capacity. Testing was conducted at this plant during June 19 to 30 and July 10 to 14, 1978.

The purpose of testing was to obtain data, before and after control devices for total organics and benzene, from the following systems:

- Benzene drying column vent
- Alkylate degasser vent
- Catalyst mix tank
- Benzene/toluene column vent.

The benzene drying column vent system consists of a condenser used to remove organics from the vent streams from the column reflux condenser and reflux decanter. The exit stream from this final condenser is routed to the plant flare system. Sampling was conducted before and after this condenser. These gas samples were collected simultaneously into flexible Tedlar^R bags at each location. Analyses were conducted on the bag samples to determine C_1-C_6 nonaromatics and benzene, toluene, xylene, ethylbenzene, and styrene. The results of these analyses are shown in Table C-1.

The alkylate degasser vent equipment consists of a polyethylbenzene scrubber and a caustic scrubber. The vent stream from the degasser is first scrubbed with a polyethylbenzene solution and then routed to a caustic scrubber. After caustic scrubbing, the vent stream is routed to

TABLE C-1. PLANT A: BENZENE DRYING COLUMN VENT SYSTEM

Species	Average Ppmv as Benzene	Average Ppmv as Species
Before Condenser		
C-1	504	2,157
C-2	17,264	3,915
C-3	1,512	2,363
C-4	209,020	274,340
C-4	478,627	628,202
C-5	8,740	8,877
C-6	45,750	38,608
Benzene	23,299	23,299
After Condenser		
C-1	4,068	17,417
C-2	34,579	78,343
C-3	1,046	1,634
C-4	89,544	117,528
C-4	119,857	157,313
C-5	18,193	18,478
C-6	379,920	320,608
Benzene	21,420	21,420

the plant flare system. Gas samples were collected from the streams before and after the caustic scrubber. Integrated samples were collected in flexible bags for organic compound analysis and inert gas analysis. The results of these analyses are shown in Table C-2.

The catalyst mix tank vent equipment consists of the catalyst storage vessel and the mix tank where the catalyst is dissolved in a polyethylbenzene solution.

The vent gases are essentially purge nitrogen streams that are used to inert the system. The vent stream is scrubbed with fresh polyethylbenzene solution prior to discharge to the atmosphere. Samples were collected to determine organic species and hydrogen chloride content of the vent stream. The results of these analysis are shown in Table C-3.

From the benzene toluene column, the vent stream from the reflux condenser and accumulator is first passed through a chilled brine condenser to remove organics prior to the steam ejector. The ejector exit stream is passed through a vacuum condenser to a hotwell. The hotwell vent stream is then passed through a final brine-chilled condenser prior to exhaust to the atmosphere. Samples were collected from the non-condensible stream prior to the ejector for organic species analysis. The results of these analyses are shown in Table C-4.

In each of the analyses, benzene, higher molecular weight hydrocarbons, and low molecular weight hydrocarbons (C_1-C_6) were determined in the field by gas chromatography with flame ionization detection. Total hydrocarbons were determined by flame ionization detection with no separation column. Oxygen, nitrogen, carbon dioxide, and carbon monoxide were determined by gas chromatography with thermal conductivity detection. Moisture analysis was conducted using EPA Method 4.

TABLE C-2. PLANT A: ALKYLATE DEGASSER VENT EQUIPMENT

Species	Ppmv as Benzene	Ppmv as Species
Before Caustic Scrubber		
C-1	447	1,914
C-2	1,928	4,368
C-3	--	--
C-4	1,760	2,310
C-4	19,804	25,993
C-5	5,348	5,432
C-6	225,139	189,991
Benzene	36,988	36,988
After Caustic Scrubber		
C-1	100	428
C-2	863	1,955
C-3	--	--
C-4	779	1,022
C-4	3,103	4,073
C-5	2,926	2,972
C-6	64,188	54,167
Benzene	33,763	33,763

TABLE C-3. PLANT A: CATALYST MIX TANK EQUIPMENT

Species	Average Ppmv as Benzene	Average Ppmv as Species
C-1	1.74	7.44
C-2	1.23	2.78
C-2	11.07	25.08
C-3	1.28	2.0
C-4	0.38	0.50
C-5	--	--
C-6	--	--
Benzene	32.47	32.47

TABLE C-4. PLANT A: BENZENE-TOLUENE COLUMN VACUUM EQUIPMENT

Species	Average Ppmv as Benzene	Average Ppmv as Species
	Before Steam Ejector	
C-1	5.032	21,544
C-2	8,520	19,304
C-2	1,575	3,569
C-3	6,746	10,541
C-4	17,166	22,530
C-4	3,084	4,084
C-5	5,308	5,391
C-6	83,724	79,653
Benzene	38,704	38,704
	After Hotwell	
C-1	1,722	7,373
C-2	7,536	17,073
C-2	6,393	14,484
C-3	4,978	7.778
C-4	16,692	21,909
C-5	8,615	8.750
C-6	78,633	66,357
Benzene	27,151	27,151

C.3.2 Plant B

This plant has a maximum production capacity of 115,000 Mg/yr of styrene from 125,000 Mg/yr of ethylbenzene. Styrene is produced at this plant by benzene alkylation to produce ethylbenzene followed by ethylbenzene dehydrogenation. Although this production method is the basic process identified in Chapter 3, some process variations do exist. The Alkar process by UOP is used by Plant B with a boron trifluoride catalyst. This plant uses a dilute ethylene stream (50 percent) to feed the process, and sends the offgases from the alkylation reaction to its boiler as fuel.[3] This process does not produce by-products or sludge and the catalyst lasts for several years.[4]

The test at Plant B was conducted during the periods of September 24 through September 28 and October 1 through October 5, 1979. Test samples were taken of the process offgases, the fuel gases feeding the superheater, and the exhaust gases of the superheater. Also, samples were taken of the fuel gas and exhaust gas of the oil heater. The purpose of this test was to determine the destruction efficiency of benzene in these combustion devices and to determine the exit benzene concentration.

The superheater at Plant B was burning fuel gas from the fuel mix drum and the dehydrogenation offgas from the styrene unit. The fuel gas from the fuel mix drum consists of natural gas and the offgas from the ethylbenzene unit alkylation reaction. The oil heater was burning the offgas/natural gas mixture from the fuel mix drum.

In the actual sampling, integrated grab samples in Tedlar^R bags were taken simultaneously at each of the two fuel inlets and at the flue gas outlet of the superheater. Integrated grab samples also were taken simultaneously at the fuel inlet and flue gas outlet of the oil heater. A modified Method 110 was used for collecting the samples. The modification was the replacement of the vacuum pump with an evacuated can. Gas flow data from the superheater outlet were obtained using Methods 1 and 2.[5]

An analysis of the samples was made with gas chromatography, flame ionization, and thermal conductivity detection. The volatile organic compounds studied were analyzed with flame ionization detection; the stationary gases were analyzed with thermal conductivity. Tables C-5 and C-6 show a summary of the test results.

C.3.3 Plant C

This plant has a production capacity of 477,000 Mg/yr of ethylbenzene and 380,000 Mg/yr of styrene and produces ethylbenzene and styrene by the basic process described in Chapter 3.

The test at Plant C was conducted during the period of May 7 through May 18, 1979. This test addressed two areas: vacuum column emissions and combustion unit control efficiencies. Sampling and analysis were conducted on the hotwell vents from the following vacuum columns: ethylbenzene recycle column, polyethylbenzene column, and styrene purification column. Multiple samples were taken at each vent, and flow measurements were taken both before and after sampling. The second part of the test focused on sampling the superheater fuel gas and flue gas. The heater fuel gas consisted of natural gas, benzene/toluene hotwell vent offgas, hydrogen separation vent offgas, and other fuel feeds from the process.

The data reported for Plant C may not be representative of the true benzene emissions from that source. During the field test, the contractor identified significant residual contamination in the sampling and analysis apparatus. Several modifications to the procedures were made during the

TABLE C-5. PLANT B: SUPERHEATER OUTLET TEST RESULTS

Run No.	2	3	4	5
Stack Benzene Concentration (ppmv at sample conditions)	0.3	0.4	<0.1	<0.1
Stack Oxygen Concentration (% $v/_v$ at sample conditions)	3.15	4.61	6.6	7.6
Moisture Content of Sample (% $v/_v$)	6.28	6.45	5.42	5.60
Corrected Stack Benzene Concentration (ppmv at 3% O_2, dry)	0.33	0.49	<0.1	<0.1

TABLE C-6. PLANT B: OIL HEATER OUTLET TEST RESULTS

Run No.	2	3	4
Stack Benzene Concentration (ppmv at sample conditions)	1.3	<0.1	<0.1
Stack Oxygen Concentration (% $v/_v$ at sample conditions)	4.16	3.63	3.98
Moisture Content of Sample (% $v/_v$)	5.53	6.45	6.24
Corrected Stack Benzene Concentration (ppmv at 3% O_2, dry)	1.52	<0.1	<0.1

test, with the overall result being that the final methods used were significantly different from Reference Method 110. Using the results of analysis of blank samples, it is estimated that contamination could have accounted for at least half, if not all, of the benzene detected in the stack samples analyzed.

Subsequent to this field test, laboratory evaluations were performed to determine the precautions necessary to eliminate contamination when measuring low-level sources. These improvements were incorporated in the contractor's techniques prior to testing at Plant B and no contamination problems were observed during that test.

Table C-7 shows the results of the superheater flue gas analyses.[6]

TABLE C-7. PLANT C: SUMMARY OF TEST RESULTS FROM SUPERHEATER OFFGAS

Run No.	1	2	3	4	5	6	7
Stack Benzene Concentration (ppmv at sample conditions)	2.8	34.0	11.9	5.5	4.4	4.23	4.5
Stack Oxygen Concentration (% $v/_v$ at sample conditions)	-	8.6	8.6	8.6	8.79	7.7	7.9
Moisture Content of Sample (% $v/_v$)	-	4.1	3.7	5.7	4.6	3.85	2.9
Corrected Stack Benzene Concentration (ppmv at 3% O_2, dry)	-	53.8	18.5	8.9	7.0	6.1	6.5

C.4 REFERENCES FOR APPENDIX C

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APPENDIX D

EMISSION MEASUREMENT METHODS

D.1 GENERAL BACKGROUND

Benzene will exist in the presence of other organics, except in the case of systems handling pure benzene. Accordingly, methods for benzene analysis consist of first separating the benzene from other organics, followed by measuring the quantity of benzene with a flame ionization detector. However, non-uniformity in procedures could exist in the following areas: (1) sample collection, (2) introduction of sample to gas chromatograph, (3) chromatographic column and associated operating parameters, and (4) chromatograph calibration.

Two possible approaches for benzene sample collection are grab samples and integrated samples. Since emission concentrations may vary considerably during a relatively short period of time, the integrated sample approach offers an advantage over the grab sample approach because emission fluctuations due to process variations are averaged automatically. In addition, the integrated approach minimizes the number of samples that need to be analyzed. For integrated samples, both tubes containing activated charcoal and Tedlar bags have been used. However, charcoal sampling tubes were designed basically for sampling ambient concentration levels of organics. Since source effluent concentrations are expected to be higher (particularly since organics other than benzene could be present), there would be uncertainty involved with predicting sample breakthrough, or when sampling should be terminated. Bag samples also would offer potentially the best precision, since no intermediate sample recovery step would be involved.

Based on the above considerations, EPA considers collecting integrated samples in Tedlar bags to be the best alternative. This conclusion is confirmed by an EPA-funded report whose purpose was to propose a general measurement technique for gaseous organic emissions.[1] Another study of benzene stability, or deterioration, in Tedlar bags was undertaken to confirm the soundness of this approach.[2] This study showed no significant deterioration of benzene over a period of four days. Consequently, the integrated bag technique was determined suitable; however, anyone preferring to use activated charcoal tubes has this option, provided that efficiency at least equal to the bag technique can be demonstrated and that procedures to protect the integrity of the sampling technique are followed.

A collected gas sample can be introduced to a gas chromatograph through use of either a gas-tight syringe or an automated sample loop. The latter approach was selected for the reference method since it has a lower potential for leakage and provides a more reproducible sample volume.

Several columns are mentioned in the literature which can be suitable for the separation of benzene from other gases;[3,4] most notable among them have been 1, 2, 3-tris (2-cyanoethoxy) propane for the separation of aromatics from aliphatics and Bentone 34 for separation of aromatics. A program was undertaken to establish whether various organics that were known to be associated with benzene in stack emissions interfered with the benzene peaks from the two columns. The study revealed that the former column was suitable for analysis of benzene in gasoline vapors and that the latter column was suitable for analysis of benzene emissions from maleic anhydride plants.[5,6] It should be noted that selecting these two columns for inclusion in Method 110 does not preclude the use of some other column(s). In fact, the method has a conditional provision for use of other columns.

Calibration has been accomplished by two techniques, the most common being the use of cylinder standards. The second technique involves injecting known quantities of 99 mole percent pure benzene into Tedlar bags as they are being filled with known volumes of nitrogen. The second technique has been found to produce equally acceptable results; both are included in Method 110.

D.2 FIELD TESTING EXPERIENCE

During the EPA field testing program, measurement studies were performed at three facilities. A variety of individual process and atmospheric emission streams were sampled. The measurement programs can be divided into three major categories: (1) vents to atmosphere from sources such as hot wells serving column vacuum producing equipment, (2) inlets to and outlets from organics recovery equipment, such as scrubbers or condensers, and (3) fuel to and flue gas from combustion devices utilizing process offgases as fuel. Each major category required different measurement approaches and presented differing sampling problems. However, the basic analytical techniques were the same. A gas chromatograph/flame ionization detector system equipped with a Poropak Q* column was used to quantify parafins and olefins in a general boiling point range designated as C1-C6. Aromatic organics, specifically benzene, toluene, xylenes, ethylbenzene, and styrene, were quantified using an OV 101* or SP1200/Bentone 34* columns as described in EPA Method 110 in a GC/FID system. Oxygen, nitrogen, carbon monoxide, carbon dioxide, and, in some cases, methane and hydrogen were determined by a gas chromatograph with a thermal conductivity detector. The major measurement differences were in sample collection and pretreatment of the samples prior to introduction to the analytical systems. Testing experience with each category are discussed below.

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*Trade Name.

(1) Atmospheric vents from hotwells: This stream generally can be characterized as a relatively low flow rate source from a small pipe, with total organics content less than ten percent by volume. The vent size was usually two to four inches. Samples are easily accessible by placing the sample probe into the end of the vent pipe. Because the total organics concentration was relatively low, the gas samples could be analyzed without any pretreatment. Volumetric flow rates were determined by using an aneometer to measure flow velocity. The aneometer was installed on the vent pipe using an adaptor section. Calibrations were performed in the laboratory to relate flow velocity and pipe size to volumetric flow.

Testing at these sources was relatively straightforward except for those cases where the hot well vent was at temperatures greater than 1,100°F. In those cases it was necessary to install a liquid knockout impinger (with no cooling) prior to the sampling bag to remove condensed water droplets. Analysis of collected condensate indicated no collection of organics in this impinger.

(2) Organics recovery equipment: These streams generally can be described as the vent from a process vessel, such as a reactor, degasser, or atmospheric or pressure distillation column, where the gas stream is either all organic or high concentration organics. This type of stream usually is routed to either a fuel or flare system and samples must be

collected through some type of drain, or purge, or sample valve existing in the pipework. Usually, the installation of a special sampling valve would require a process shutdown.

Gas samples were collected using preconditioning systems in some cases. At one facility, liquid carryover and condensing water and organics required that an ice-cooled condenser train be used prior to the gas sample bag. At other locations, a simple knockout impinger was all that was required, or no pretreatment at all was necessary. In those cases where condensers or traps were used, the collected liquids were recovered and analyzed. In those cases where a cooled condenser train was used, either as a sample pretreatment or to measure moisture content of the stream, a two-phase liquid was formed in the condenser during sampling. This was due to condensed organics in addition to water in the condenser.

Prior to analysis, it was necessary to dilute the samples. Metered flows of concentrated sample and nitrogen were mixed into a second flexible bag. Nominal dilution ratios of 10:1 were used. If further dilution was necessary, the mixture resulting from the 10:1 dilution was again diluted to obtain a 100:1 final mixture. Dilution ratios were confirmed by either performing the dilution on a known calibration standard and analyzing before and after dilution, or by analyzing a component (CO_2, CH_4, etc.) of the sample and all dilutions.

The major analysis difficulties encountered were: on one test, calibration standards were not available for the concentration range encountered and it was necessary to assume linear extrapolation of lower level calibrations (a dilution apparatus was not available at that test); and in some cases where C-1 through C-6 concentrations were much greater than the benzene concentration, there were some peak overlaps that caused benzene results repeatability to be poor.

Volumetric flow rates were determined by plant process instrumentation when available. An existing orifice meter was used to determine flow, and temperature and pressure were obtained from process instrumentation. In those cases where flow meters did not exist, no direct measurement was possible since a process shutdown was necessary to install a meter. Also, in one case it was not possible to use an existing orifice meter because entrained liquids in the gas stream caused erratic pressure differential readings.

(3) Combustion Devices: Tests were performed to obtain a complete fuel analysis and a complete flue gas analysis, including specifically benzene, at three combustion devices.

Fuel samples were obtained using the standard flexible bag technique, with the exception that the fuel pressure was used to fill the bags. Due to the fuel distribution arrangement at one site it was necessary to collect samples of two different fuels that were fired in the process heater since no mix drum was used in the system. After collection, the samples were diluted to a nominal 100:1 ratio and analyzed for organics. Fixed gases (N_2, O_2, CO, CO_2) were determined from the undiluted sample. Two major problems were encountered. First, even after a 100:1 dilution, the methane content was erroneously determined using the GC/FID system. Apparently the combination of high concentration and fast elution time from the column causes saturation of the FID. This problem occurred during the first combustion device test and was not confirmed until after testing was completed. This difficulty was corrected for subsequent tests by including a specific methane analysis by GC/thermal conductivity. Second, it was observed that where hydrogen makes up a significant portion of the fuel, analysis for hydrogen and dilutions for organic analysis must be performed as rapidly as possible. The permeation rate of hydrogen through flexible bags is high and, after times as short as one hour, essentially all of the hydrogen present will be lost.

The sampling and analysis of the flue gas stream presented a major problem during the first combustion device test. After the first test run at that unit, it became apparent that the Method 110 sampling apparatus had been contaminated during earlier tests and could not be adequately cleaned. The sampling system was changed so that essentially grab samples were collected into glass flasks. However, the subsequent test results included higher than expected organic results and inconsistencies. During the analysis program, blank samples were prepared using the sampling techniques with pure grade nitrogen as the gas source. Significant blank levels were observed. Also, it was not possible to sufficiently clean the chromatograph sample injection system using air or nitrogen. Laboratory evaluations after the field test identified the following information:

(a) After exposure to high level aromatics, the sampling apparatus cannot be adequately cleaned by simple purging.

(b) Glassware exposed to aromatic compounds cannot be cleaned using purging and solvent rinses alone. (This affected both the glass flasks used for sampling and the glass syringe used for sample injection.)

(c) An unheated sample loop on the gas chromatograph does not purge to zero quickly.

(d) The syringe used for sample injection was too small to adequately flush and fill the GC sample loop.

Because of the contamination problems encountered during the first site test, changes were made to the preparation, sampling, and analysis procedures prior to the tests at the next two sites:

(a) New sample bags were obtained and analyzed individually for contamination prior to the field test.

(b) The sample acquisition tubing arrangement was changed so that no part was reused from one test to the next.

(c) A heated sample loop and a sample pumping system were added to the GC system.

During the performance of tests at the next two sites, the ability to obtain essentially zero system blanks during the field analysis confirmed that these modifications were adequate to avoid invalid results due to contamination. These requirements are specifically addressed in Method 110.

The volumetric flow rate of the fuel was determined from plant instrumentation. Since in two of the three units tested it was not possible to measure a flue gas flow rate, a combustion calculation using the fuel and flue gas analyses was performed. This calculation was used to determine a dilution factor for combustion so that a mass-basis benzene removal efficiency could be calculated.

D.3 EMISSION MONITORING

No emission monitoring instrumentation, data acquisition, and data processing systems that are specifically installed to measure benzene emissions in atmospheric vents at ethylbenzene/styrene (EB/S) facilities have been identified. However there are commercial systems available that incorporate automated gas chromatography with flame ionization detection and are equipped with automatic data processing systems. These have been specifically applied to ambient process area measurements for occupational health and safety reasons. Various compounds or combinations of compounds have been measured, including benzene. Since the only major differences between systems designed for different compounds are the separation column selected and the operating cycle time, there is no technical reason why currently available instrumentation cannot be applied to monitoring benzene emissions.

EPA has not developed performance specifications for benzene emissions monitors. The following criteria are recommended for the purposes of this application:

(1) The monitoring system should consist of a sample acquisition system which continually extracts a sample from one or more sources and these samples are to be analyzed by gas chromatography using flame ionization detection (essentially an automated version of the reference test method, EPA Method 110).

(2) If desired, the chromatographic separation step may be deleted and direct measurement of total organics by flame ionization detection, non-dispersive infrared spectrometry, or equivalent or alternative procedures may be used if all organics are assumed to be benzene.

(3) The emission monitoring system may be used to evaluate more than one emission point but at least one data result for each location should be available in each one-hour period. Assuming a 15-minute cycle time for analysis, this would allow the concurrent monitoring of four emission points. If a faster cycle time or fewer points are monitored, then the number of results per hour would be greater.

(4) The analyzer system should be zeroed and calibrated daily. A gas with less than 0.1 ppm benzene content is to be used for zeroing and a five

ppm benzene mixture is to be used for calibration. The calibration mixture may be prepared as a cylinder gas or by manual procedures as provided in EPA Method 110.

The resulting emission data would usually be on a wet basis as present at the emission point. It is recommended that the facility be allowed to develop an average moisture content value for the purposes of correction to a dry benzene concentration basis.

It is recommended that for the purpose of identifying and reporting excess emissions a three-hour average be used. This is consistent with the actual sampling time over which a performance test is conducted. The arithmetic average of the benzene concentration data over three contiguous one-hour periods represents the three-hour average.

It is estimated that the installed capital cost of an emission monitoring system serving from one to four emission locations would range from $30,000 to $50,000 depending on the system chosen and the installation difficulty encountered. The annual operating cost can vary significantly, depending on the time requirements for calibration and maintenance, and is estimated to be between $5,000 and $20,000/year. The operating cost does not represent a total annualized cost.

For those applications where an enclosed combustion device, such as an incinerator, process heater, or boiler, is used to control the affected emissions, it is recommended that monitoring of operations be used instead of direct benzene emission monitoring. Suggested parameters that should be monitored are the flow of the affected emission streams, the internal temperature of the combustion device, and the oxygen content of combustion device flue gas.

EPA has not developed performance specifications for flow/meters or temperature measurement devices; therefore, manufacturers' specifications and installation, calibration, and maintenance directions are the only available criteria for evaluation of the acceptability of any particular device. For the purposes of operations monitoring, a flow measurement device with a stated accuracy of ± 5 percent and a temperature measurement device with an accuracy of ± 2 percent are adequate.

EPA has developed performance criteria for oxygen analyzers for those facilities affected by New Source Performance Standards emission monitoring requirements.[7] However, these specifications only include stability criteria and do not require a specified accuracy. Since the oxygen measurement equipment in this application is an operations monitor and not an emission monitor, it is recommended that the existing NSPS criteria for oxygen analyzers not be applied.

The only recommended operating specification is that the analyzer should be calibrated weekly using either air or a prepared cylinder standard.

The operating standards to be used as references are those existing during the required emission test. Any time after the emission test that the average process vent stream flow, combustion device temperature, or flue gas oxygen content varies by more than a selected amount indicates an excess emission interval. The time to be used for computing these averages is three hours.

The estimated installed cost of each process measurement and recording device combination is from $1,000 to $5,000. Therefore, assuming one flow, temperature, and oxygen monitor, the total installed cost would be from $3,000 to $15,000, depending on installation difficulty. The annual operating cost of all process monitors combined is estimated to be from $500 to $1,500. However, in many EB/S facilities, an oxygen analyzer is currently installed and temperature measurement devices are installed in essentially all facilities. In most cases, the only additional operations monitoring equipment required would be flow devices.

D.4 EMMISSION TEST METHODS

The recommended emission test procedure for determining benzene emission concentrations is EPA Method 110. An integrated sample from the source is drawn into a flexible bag over a one-hour sampling period. A gas chromatograph/flame ionization detector system equipped with a column selected for separation of benzene from the other organics present is used for analysis. Unless a different value is known, the moisture content of the sample is assumed to be the saturation point at the sample storage temperature at the time of analysis. The moisture content is used to correct the measured benzene concentration to a dry basis. Three one-hour samples are collected and analyzed.

For those applications where enclosed combustion is used as the control technique, it is necessary to determine the oxygen content of the collected sample. The recommended analysis procedure is by Orsat apparatus, as described in EPA Method 3 (40 CFR 60, Appendix A). The oxygen concentration in the sample is used to convert the measured benzene concentration (dry basis) to a reference basis of three percent oxygen.

Subpart A of 40 CFR 61 (National Emission Standards for Hazardous Air Pollutants) requires that facilities subject to provisions of that part provide sampling ports adequate for the applicable test methods and platforms, access, and utilities necessary to perform testing at those ports.

Assuming that the test location is near the analytical laboratory and that sample collection and analytical equipment and supplies are on hand, the cost of field collection, laboratory analysis, and reporting of benzene emissions from a single source is estimated to be \$2,500 to \$3,500 for a compliance test effort. This estimate assumes an overall labor cost of \$25/person-hour and is based on triplicate samples and triplicate analyses of each sample. This estimate could be reduced by as much as 50 percent per source if several test programs are conducted concurrently. In addition, if the facility has established in-house sampling and analytical capabilities, the cost of a compliance test effort could be lower.

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APPENDIX E

METHODOLOGY FOR ESTIMATING MORTALITY AND MAXIMUM RISK FROM EXPOSURE TO BENZENE EMISSIONS FROM ETHYLBENZENE/STYRENE PLANTS

APPENDIX E

METHODOLOGY FOR ESTIMATING MORTALITY AND MAXIMUM RISK FROM EXPOSURE TO BENZENE EMISSIONS FROM ETHYLBENZENE/STYRENE PLANTS

E.1 INTRODUCTION

This appendix describes the methodology used in estimating leukemia mortality attributable to population exposure to benzene emissions from ethylbenzene/styrene (EB/S) plants. The appendix is presented in three sections:

- Section E.2 summarizes and references reported health effects from benzene exposure. The major reported health effect is leukemia. Mortalities cited include only the estimated leukemia deaths attributable to exposure to benzene emissions from existing EB/S plants although other, sometimes fatal effects are known to result from benzene exposure.
- Section E.3 describes the method used to estimate the population residing within 20 km of existing EB/S plants.
- Section E.4 describes the methodology for estimating benzene emissions from a model plant, calculating expected population exposures, and estimating leukemia deaths attributable to benzene emissions from 13 existing U.S. plants.

E.2 SUMMARY AND OVERVIEW OF HEALTH EFFECTS

E.2.1 Health Effects Associated with Benzene Exposure

Numerous occupational studies over the past 50 years have documented severe health effects in humans from prolonged inhalation exposure to benzene. Some 300 studies of the health effects of benzene have recently been reviewed and analyzed in terms of application to low-level ambient benzene exposures that might occur in a population residing near a source of benzene emissions.[1]

The reviewers concluded that benzene exposure by inhalation is strongly implicated in three pathological conditions that may be of public health concern at environmental exposure levels: (1) leukemia (a cancer of the blood-forming system), (2) cytopenia (decreased levels of one or more of the formed elements in the circulating blood), and (3) chromosomal aberrations.

Leukemia is a neoplastic proliferation and accumulation of white blood cells in blood and bone marrow. The four main types are acute and chronic myelogenous leukemia and acute and chronic lymphocytic leukemia. The causal relationship between benzene exposure and acute myelogenous leukemia and its variants in humans appears to be established beyond all reasonable doubt.[1]

The term "pancytopenia" refers to diminution of all formed elements of the blood and includes the individual cytopenias: anemia, leukopenia, thrombocytopenia, and aplastic anemia. In mild cases, symptoms of pancytopenia are such nonspecific complaints as lassitude, dizziness, malaise, and shortness of breath. In severe cases, hemorrhage may occur and death may result from hemorrhage or massive infection. Patients with pancytopenia may subsequently develop fatal acute leukemia.

Chromosomal aberrations include chromosome breakage and rearrangement and the presence of abnormal cells. These aberrations may continue for long periods in hematopoietic and lymphoid cells. The significance of these aberrations is not fully understood. However, aberrant cells have been observed in individuals exposed to benzene who have later developed leukemia. Furthermore, some types of chromosomal aberrations may be inheritable. In one study (too recent to include in the review[1]), workers exposed to 2.1 ppm benzene for four years showed a statistically significant increase in chromosomal aberrations (as high as tenfold) over those in unexposed controls.[2]

The review concluded that humans may be the only species yet observed to be susceptible to benzene-induced leukemia.[1] Evidence for production of leukemia in animals by benzene injection was considered nonconclusive. Although other effects, including pancytopenia, have been widely observed,[1] benzene exposure by oral dosing, skin painting, or inhalation has not been shown to produce leukemia or any other type of neoplastic diseases in test animals.

E.2.2 Benzene Exposure Limits

The health effects described above are based on benzene exposure at occupational levels. That is, the benzene exposure levels associated with the effects have been high (ten ppm up to hundreds of ppm benzene, except in a few cases of exposures to two to three ppm benzene) or they are unknown.

Benzene exposure was first associated with health effects in occupational settings. Therefore, initial attempts to limit benzene exposures were aimed at occupational exposures. With the greatly expanded use of benzene after 1920 and recognition of its toxic effects, several occupational exposure limits were established in the United States.[3] These limits, originally in the range of 75 to 100 ppm, were successively lowered as more information on benzene toxicity became known. For example, the American Conference of Governmental Industrial Hygienists (ACGIH) recommended a benzene threshold limit of 100 ppm in 1946, 50 ppm in 1947, 35 ppm in 1948, 25 ppm in 1949, and ten ppm in 1977.[3,4] The National Institute for Occupational Safety and Health (NIOSH) recommended an exposure limit of ten ppm in 1974 and lowered it to one ppm in 1976.[5] The current Occupational Safety and Health Administration's (OSHA) permissible exposure limit is ten ppm[6] (a more stringent limit of one ppm is currently in litigation[7]).

Occupational exposure limits were initially established to protect workers from adverse changes in the blood and blood-forming tissues. The most recently recommended or pending limits of one ppm and ten ppm are based on the conclusion that benzene is leukemogenic in man (NIOSH[5] and OSHA[8], respectively) or a suspected carcinogen (ACGIH[4]) in humans.

E.2.3 Health Effects at Environmental Exposure Levels

Very little information is available on health effects of nonoccupational exposures of the general populace to benzene. Virtually all of the studies cited[1,2] were on the working population (mostly males) exposed to higher than ambient benzene levels on a work cycle. Applying these studies to chronic (24 hours per day), low-level exposure and to the general population (including infants, the ill, and the elderly) requires extrapolation.

The recent analysis of benzene health effects concluded that the evidence of increased risk of leukemia in humans from exposure to benzene for various time periods and concentrations was overwhelming, but that data were not adequate for deriving a dose-response curve.[1] However, EPA's Carcinogen Assessment Group (CAG), acknowledging the absence of a clear dose-response relationship, has estimated the risk of leukemia in the general population from low-level benzene exposure.[9] Data from three epidemiological studies of leukemia in workers (mostly adult white males) were used to estimate the risk of developing leukemia.[9] The annual risk factor derived by CAG for benzene-induced leukemia is 0.34 deaths per year per 10^6 ppb-person years. CAG calculated the 95 percent confidence intervals for this risk factor to be 0.17 to 0.66 if exposure estimates in the three studies are correct and 0.13 to 0.90 if exposure estimates are within a factor of two.

A no-threshold linear model was used to extrapolate this estimated risk to the low levels (below five to ten ppb) to which some populations may be exposed. Use of a "linear" model means that the model would predict the same number of leukemia deaths among three million people exposed to one ppb benzene as among six million people exposed to 0.5 ppb.

The risk factor was used in estimating the number of leukemia deaths as attributable to benzene emissions from EB/S plants. Other effects of benzene exposure (including fatalities from causes other than leukemia) were not included in the estimated number of deaths. The risk factor equated one leukemia case to one death; that is, each case was presumed fatal.

Four sources of uncertainty exist in applying the risk factor: (1) the retrospective occupational exposure estimates may be inaccurate (howver, CAG has estimated the confidence limits for this source of error); (2) the true dose-response relationship for benzene exposure may not be a linear, no-threshold relationship at the low concentrations to which the general population may be exposed; (3) the risk factor includes only leukemia deaths and not other health risks; and (4) the risk factor assumes that the susceptibility to leukemia associated with a cohort of white male workers is the same as that associated with the general population, which includes men, women, children, infants, the aged, non-whites, and the unhealthy. No quantitative estimate of th error in the risk factor due to the latter three uncertainties has been attempted.

E.3 POPULATION DENSITY AROUND EB/S PLANTS

The population residing within 20 km of each EB/S plant was determined from the 1970 Bureau of the Census Master Enumeration District List (Med List).

Each plant site was located by latitude and longitude on a grid system having grids of approximately ten square kilometers (km). The population was determined from the Med List for each grid block within 20 km of each plant site.[10]

Circles of radii of 0.1, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 10.0, and 20.0 km were overlaid on each grid and the population within each annular (ring or doughnut-shaped) area was determined. Where grid blocks overlapped two annular areas, the population was assumed to be uniformly distributed and was assigned proportionately to each area. The population in each annular area was considered to be the population exposed to the estimated benzene concentration at the midpoint of that area. The estimated total population exposed as a function of distance from the plant site is reported in Table E-1. (All tables are presented at the end of this appendix.)

The method used contains potential sources of error. First, the assumption of uniform population distribution within grid blocks and annular areas may not hold true. For urban areas the assumption is valid, but it may introduce a degree of error for rural areas (which is the case with one plant) 10 to 20 km from the site. Another potential source of error is the use of 1970 population data. However, these are the latest available data in the form required for the model.

E.4 POPULATION EXPOSURES, RISKS, AND MORTALITY

E.4.1 Summary of Methodology

A typical (or "model") EB/S plant was developed based on 8,000 hours of operation per year for continuous process vents and fugitive emissions and 8,760 hours per year for storage and excess emissions. Four continuous process benzene emission rates exist for the model plant and each reflects the use of specific benzene emission control equipment. These emission rates are 69 kg/hr for the model plant with uncontrolled process vents, 9.8 kg/hr for the model plant equipped with a condenser and absorption tower system, 3.9 kg/hr for the model plant with a combination condenser/absorption tower/flare, and 0.32 kg/hr for the model plant employing an existing boiler to combust the process vent waste streams. In all four cases, fugitive and excess emissions, with emission rates of 0.0009 and 0.84 kg/hr, respectively, were assumed uncontrolled for all four process emission rates. A benzene storage emission rate of 27.0 kg/hr reflects the current level of control for this source.

The Industrial Source Complex Dispersion (ISCD) model, urban mode two, was used to estimate annual average benzene concentrations for the four continuous process emission rates out to 20 km from the model plant. Houston meteorological data, which best represent weather conditions for most EB/S plants, were used in the dispersion model.

The area over which the benzene concentrations are estimated is a polar coordinate map. The emissions source (plant) is at the center and, depending on input variables, such as nature of the emission plume, local meteorological conditions, and terrain, benzene dispersion characteristics follow predictable patterns. The ISC model predicts approximate benzene concentrations at any distance from the plant complex up to 20 km. Distances of 0.16, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 10.0, and 20.0 km were chosen for location of receptor rings. Graphically, they are best described as nine imaginary concentric circles surrounding the source along which, at equidistant intervals, are 30 receptor points at which benzene concentrations are predicted.

Benzene concentrations predicted at each of the 30 receptor points were arithmetically averaged for each ring. This mean annual average benzene concentration for each of the nine ring distances was then plotted on "log-log" graph paper. A curve fitted to these points shows that benzene concentrations decrease at a predictable rate with distance from the source.

Population values were given for each of the annular spaces between the receptor rings and were assumed to be equally distributed throughout that space. Since benzene concentrations continuously are decreasing over distance, an average concentration had to be determined for each annular space. This was done by calculating the area midpoint for each annular space and interpolating the benzene concentration on the curve corresponding to the calculated midpoint distance. Except for fugitive emissions which are independent of plant capacity, dispersed benzene concentrations of that model plant equipped with controls most closely resembling those in the existing plant were then scaled to reflect actual plant capacity for existing EB/S plants.

The population (1970) around each actual plant was correlated with benzene concentrations of each corresponding plant to yield benzene dose in ppb-person years. The methods for determining populations around EB/S plants are described in Section E.3 of this appendix.

From health effects data, the EPA Carcinogen Assessment Group derived a leukemia risk factor of 0.34 deaths per year per 10^6 ppb-person years from exposure to benzene. The methodology for estimating the leukemia risk factor is described in Section E.2.3 of this appendix. The leukemia deaths per year attributable to exposure to benzene from EB/S plants were estimated by multiplying "0.34 deaths per year per 10^6 ppb-person years" times the exposure in "ppb-person years."

Maximum lifetime (70 years) risk is the probability that an individual will contract leukemia from lifetime exposure to the highest maximum annual average benzene concentration downwind of a plant. The 70-year lifetime risk factor consists of multiplying the annual CAG risk factor (0.34 deaths per year per 10^6 ppb-person years) by 70 to yield 2.38×10^{-5}. The product of this lifetime risk factor, the highest maximum annual average benzene concentration, and one person exposed to that concentration yields the maximum lifetime risk of contracting leukemia for that individual.

This appendix provides methodology and examples for risk and death calculations for existing EB/S plants, assuming current control levels for continuous process and storage emissions and uncontrolled levels for fugitive and excess emissions. Leukemia incidence and maximum risk calculations for each regulatory option can be done similarly according to the methodology presented by using the appropriate emission concentrations and scaling factors listed for that option in Tables E-2a, E-2b, and E-3, respectively.

Calculations for this chapter were performed by computer and intermediate steps are accurate to four decimal places. However, the numbers presented in the tables have been rounded to two decimal places for convenience. Hand calculations therefore may result in a slight deviation from tabulated values.

E.4.2 Continuous Emissions

E.4.2.1 Estimates of Leukemia Deaths

The general equation for estimating leukemia deaths attributable to continuous benzene emissions (including fugitive and storage emissions) from a particular plant (e.g., plant X) under current controls is:

$$D_x = (R) \sum_{i = 0.1\text{-}0.3}^{10\text{-}20} (P_i)(B_i) \qquad (1)$$

in which

D_x = estimated number of leukemia deaths per year due to benzene emissions from the plant (e.g., plant X)

R = the CAG risk factor (0.34 deaths per year per 10^6 ppb-person years)

P_i = population in area (i) around plant X

B_i = mean annual average benzene concentration (ppb) in area (i) around plant X for current control level (including uncontrolled emissions from fugitive sources)

i = the particular area in which P_i and B_i occur

Σ = summation of deaths from all areas (i).

Values for P_i are found in Table E-1. Tables E-2 and E-3 were used in calculating values for B which are presented in Tables E-4 to E-7. Table E-8 presents total exposure $[\Sigma(P_i)(B_i)]$ for each source.

Leukemia deaths per year were estimated for each plant, using equation 1. The total estimated number of leukemia deaths per year attributable to continuous benzene emissions from all plants was determined by the equation:

$$D_t = D_1 + D_2 \ldots + D_{13} \qquad (2)$$

The total number of estimated leukemia deaths per year attributable to benzene emissions from each EB/S plant at current control levels is presented in Table E-9.

E.4.2.2 Example of Leukemia Death Calculation

Values in Table E-9 were determined according to the same methodology as the following example calculations for the Cos-Mar Plant. The following parameters are assumed:

$$R = 0.34 \times 10^{-6} \text{ (CAG annual risk factor)}$$

$$D_x = (0.34 \times 10^{-6}) \sum_{i = 0.1\text{-}0.3 \text{ km}}^{10\text{-}20 \text{ km}} (P_i)(B_i)$$

P_i values for each area (i) around this plant are taken from Table E-1. Model plant concentrations (B_i) are from the plant equipped with condenser/absorption tower/flare to reflect existing process control levels in the

Cos-Mar facility (Table E-2). B_i values for each area (i) around this plant are taken from Table E-6.

AREA (i)	P_i (persons)	B_i (ppb)	$P_i \times B_i$
0.1- 0.3	15	15.5	233
0.3- 0.5	27	11.6	313
0.5- 0.7	41	8.23	337
0.7- 1.0	87	5.72	498
1.0- 1.5	210	3.36	706
1.5- 2.0	310	2.05	636
2.0-10.0	7,650	0.25	1,913
10.0-20.0	60,100	0.07	4,207
			8,843

Total Deaths $D_x = (.34 \times 10^{-6})(8843) = 3.0 \times 10^{-3}$*

E.4.2.3 Estimate of Leukemia Risk

The methodology used for estimating maximum lifetime risk involves determining the highest maximum annual average benzene concentration at any receptor at any ring distance out to 20 km from the model plant. Table E-2a shows the highest maximum annual average benzene concentration for the model plant (1) under uncontrolled conditions, (2) with condensers and absorbers, (3) with a condenser/absorber/flare system, and (4) with boilers. The highest maximum annual average concentration for the uncontrolled model plant is 126 ppb. This figure is a composite of uncontrolled process and fugitive emissions, and existing controls for storage emissions. To obtain the highest maximum annual average concentration for existing plants the model plant concentration which best reflects the emission rate and control equipment used by each existing plant is factored for the styrene capacity of the existing plant (Table E-3). The factored highest maximum benzene concentration (Table E-10) is then multiplied by the CAG risk factor of

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*Example calculation result differs slightly from that found in Table E-9 due to rounding.

2.38×10^{-5} to yield the maximum risk (Table E-11) of contracting leukemia assuming that an individual is exposed to that benzene concentration for a period of 70 years.

Maximum lifetime risk

= (B_{max}, the highest maximum per-plant annual benzene concentration in ppb)

x (R, the risk factor (0.34×10^{-6})) x (70 years exposure) = 2.38×10^{-5} deaths per lifetime per ppb-person years

= (2.38×10^{-5})(highest maximum B_i in ppb)

E.4.2.4 Example of Leukemia Risk Calculation

For the Cos-Mar plant, a highest maximum annual average benzene concentration of 40.1 ppb resulting from fugitive and storage emissions is predicted to occur 0.16 km downwind of the plant. Concurrently, a highest maximum annual average benzene concentration of 9.0 ppb resulting from continuous process emissions is predicted to occur 0.5 km downwind of the plant.

In order to obtain the combined highest maximum annual average benzene concentration for the plant, the more significant source contributor to the combined concentration is determined. (In this case, fugitive and storage emissions predominate.) The remaining contributing concentration (from process vents) predicted to occur at that receptor point are added to the primary emissions.

In this example, the actual process vent contribution to the maximum combined benzene concentration is less than the 9.0 ppb predicted to occur at 0.5 km from the plant because, at 0.16 kilometers, the bulk of the emission plume emanating from the tall flare stack has not traveled a sufficient horizontal distance to reach maximum ground level benzene concentration.

The maximum lifetime risk to an individual residing 0.16 km from the plant is calculated as follows:

$$\begin{array}{lclcl} \text{Max lifetime risk} & = & \text{40.1 ppb} & + & \text{0.5 ppb} \\ & & \text{Max B. due to} & & \text{Max B. due to} \\ & & \text{fugitive and storage} & & \text{emissions from continuous} \\ & & \text{emissions at 0.16 km} & & \text{process vents at 0.16 km} \end{array}$$

$$\text{X} \quad 2.38 \times 10^{-5} \text{ (risk factor)} = 9.7 \times 10^{-4}$$

E.4.3 Excess Emissions

E.4.3.1 Estimates of Leukemia Deaths from Excess Emissions

Ambient benzene concentrations resulting from emissions due to malfunction of control or process equipment, startup, and shutdown were modeled exclusive of continuous process, fugitive, and storage emissions. These excess emissions were modeled in a similar fashion as were the continuous process emissions, i.e., a completely uncontrolled model plant of 300,000 Mg/yr styrene capacity was assumed. The benzene concentrations from the model plant were factored according to plant capacity to predict benzene concentrations, at distance, for each existing plant (Table E-7). Unlike adjustments made for the continuous process emissions, where existing control equipment in each plant was known, factoring for excess emission rates for existing plants considered styrene capacity only because current levels of excess emission control are unknown. Therefore, excess emissions from existing EB/S plants were assumed uncontrolled for this analysis.

Incidence of leukemia deaths attributable to excess emissions is derived in the same manner as that for continuous emissions. Average exposure is calculated for each of the eight annular distances for each plant to a distance of 20 km (Table E-7). Table E-8 presents total exposure from excess benzene emissions as well as exposure from all sources. Table E-9 presents estimated incidence of deaths due to benzene exposure from excess emissions and from all other sources.

E.4.3.2 Estimates of Leukemia Risk from Excess Emissions

Maximum lifetime risk from exposure to excess emissions is determined by selection of the maximum annual average benzene concentration occurring at any one of the 30 model plant receptors on any of the nine rings around the model plant (Table E-2a). This concentration is factored (Table E-3) to reflect existing plant capacity and the scaled benzene concentration (Table E-10) is multiplied by the CAG risk factor to yield the maximum risk to an individual of contracting leukemia due to lifetime exposure (Table E-11). Again, the risk estimated for lifetime exposure to excess emissions assumed uncontrolled plants. Table E-10 presents maximum risk estimates for an individual due to a lifetime exposure to excess emissions from one plant.

E.4.4 Validity of Estimates

Incidence and risk estimates presented in Tables E-9 and E-11 are the actual midpoints of the ranges presented in Tables E-12 and E-13. These ranges are based on a 95 percent confidence interval that assumes the estimated concentrations to which the workers are exposed are within a factor of two.[9] The ranges presented here represent the uncertainty of estimates made concerning the levels to which workers were exposed in the Infante, Aksoy, and Ott studies that served as the basis for developing the benzene risk factor.

In addition, other sources of uncertainty exist that are not quantitatively expressed. The number of deaths was calculated based on an extrapolation of leukemia risk associated with a healthy white male cohort of workers to the general population, which includes men, women, children, infants, the aged, non-whites, and the unhealthy. Furthermore, some uncertainty is inherent in the benzene levels predicted by the dispersion modeling to which people in the vicinity of EB/S plants are exposed. Moreover, only one effect of benzene was considered, i.e., leukemia. Benzene has also been causally implicated in aplastic anemia, cytopenias, and the development of chromosomal aberrations. Finally, the benefits to the general population of controlling other hydrocarbon emissions from EB/S manufacture are not quantified.

TABLE E-1. POPULATION RESIDING AROUND EB/S PLANTS
(thousands of persons)

PLANT	DISTANCE (km)							
	0.16-0.3	0.3-0.5	0.5-0.7	0.7-1.0	1.0-1.5	1.5-2.0	2.0-10.0	10.0-20.0
Am. Hoechst	0.34	0.60	0.90	1.91	4.68	6.39	158.0	118.7
Amoco	0.34	0.60	0.89	1.90	4.66	6.16	44.0	87.8
Arco, PA	0.25	0.46	0.69	1.46	3.73	4.27	116.0	136.7
Arco, TX	0	0	0	0	0	1.04	86.0	38.1
Cos-Mar	0.015	0.027	0.041	0.087	0.21	0.31	7.65	60.1
Dow, TX	0.045	0.081	0.12	0.26	0.64	0.89	32.8	14.4
Dow, MI	0.28	0.50	0.75	1.60	4.12	4.37	32.9	35.7
El Paso	0	0	0	0	0	0.388	72.2	18.7
Gulf	0	0	0	0	0	0	5.19	36.9
Monsanto	0.34	0.60	0.89	1.90	4.66	6.16	44.0	87.8
Oxirane	0	0	0	0	0	0.159	55.6	387.6
Sun Oil	0.14	0.25	0.38	0.81	1.98	3.20	122.4	85.4
U.S. Steel	0.12	0.21	0.31	0.66	1.63	4.20	399.1	691.3

TABLE E-2a. PREDICTED MEAN ANNUAL AVERAGE BENZENE CONCENTRATIONS IN PARTS PER BILLION (ppb) FOR MODEL PLANT

CONTROL	DISTANCE (km)							
	0.16-0.3	0.3-0.5	0.5-0.7	0.7-1.0	1.0-1.5	1.5-2.0	2.0-10.0	10.0-20.0
Uncontrolled Process Emissions	49.9	42.7	22.4	13.2	7.26	3.78	2.38	0.18
Process Emissions Controlled With Condenser/Absorption Tower	8.2	4.2	2.3	1.4	0.73	0.40	0.04	0.012
Process Emissions Controlled With Condenser/Absorption Tower/Flare	0.11	0.32	0.325	0.268	0.166	0.105	0.013	0.0035
Process Emissions Controlled With Boiler	0.001	0.015	0.034	0.041	0.038	0.029	0.005	0.002
Fugitive and Storage Emissions[a] --	7.05	3.76	2.00	1.12	0.60	0.34	0.038	0.014
Excess Emissions -- Uncontrolled	1.60	1.05	0.60	0.36	0.21	0.12	0.01	0.004

[a] Fugitive emissions are assumed uncontrolled. The storage emission rate is based on partial control, e.g., some storage tanks fitted with a floating roof, and reflects current industry control levels for benzene storage tanks.

TABLE E-2b. PREDICTED HIGHEST MAXIMUM ANNUAL AVERAGE BENZENE CONCENTRATION IN PARTS PER BILLION (ppb) FOR THE MODEL PLANT

Emissions	Uncontrolled Plant	Plant w/ Condenser/ Absorption Tower	Plant w/ Condenser/ Absorption Tower/Flare	Plant w/ Boiler
Process	106[a]	20.7[a]	0.679[b]	0.095[c]
Fugitive and Storage[a]	20.0	20.0	20.0	20.0
Excess Emissions[a]	3.5	3.5	3.5	3.5

[a] Occurs at 0.16 km downwind of plant.

[b] Occurs at 0.5 km downwind of plant. For the combined source impact, model plant process vent contribution at 0.16 km is approximately 0.04 ppb.

[c] Occurs at 1.0 km downwind of plant. For the combined source impact, model plant process vent contribution at 0.16 km is approximately 0.00015 ppb.

TABLE E-3. SCALING FACTORS

PLANT	STYRENE Capacity (10^3 Mg/yr)	CONTINUOUS EMISSIONS Process (Current Control)	Process (Option A)	Process (Option B)	Process (Option C)	Fugitive and Storage[a]	EXCESS EMISSIONS[a]
Am. Hoechst	450	0.6	0.9	1.5	0.6	1.6	1.75
Amoco	380	0.04	0.04	0.5[c]	0.5	1.2	1.27
Arco, PA	200	0.13	0.13	0.13	0.1	0.2	0.67
Arco, TX	227(EB)[d]	0.5	0.5	0.5	0.02	0.7	0.76
Cos-Mar	590	13.0[b]	3.4[b]	2.0	0.8	2.0	1.97
Dow, TX	680	0.3	0.4	0.6	0.9	2.3	2.27
Dow, MI	181	0.12	0.12	0.12	0.01	0.1	0.60
El Paso	115	0.4[b]	0.06[b]	0.06	0.1	0.5	0.38
Gulf	272	5.4[b]	1.2[b]	0.9	0.4	0.9	0.91
Monsanto	680	2.0[c]	2.0[c]	2.0[c]	2.0	2.0	2.27
Oxirane	454	9.0[b]	1.5[b]	1.5	0.6	1.5	1.51
Sun Oil	36	0.03	0.03	0.05[c]	0.05	0.3	0.12
U.S. Steel	54	0.01[c]	0.01[c]	0.01[c]	0.01	0.1	0.18

[a] Fugitive emission sources as well as excess emissions sources are assumed uncontrolled. Storage tank emission sources are partially controlled and reflect current control levels.

[b] Use mean annual average benzene concentration from model plant with condenser/absorption tower/flare controls.

[c] Use mean annual average benzene concentration from model plant with boiler controls.

[d] (EB)=ethylbenzene capacity.

TABLE E-4. SCALED MEAN ANNUAL AVERAGE BENZENE CONCENTRATIONS IN PARTS PER BILLION (ppb) AT DISTANCE FROM PLANT IN KILOMETERS (km)
PROCESS VENT CONTRIBUTION
CURRENT CONTROL LEVEL

PLANT	DISTANCE (km)							
	0.16-0.3	0.3-0.5	0.5-0.7	0.7-1.0	1.0-1.5	1.5-2.0	2.0-10.0	10.0-20.0
Am. Hoechst	30.2	18.6	9.78	5.52	3.00	1.74	0.18	0.05
Amoco	2.01	1.24	0.65	0.37	0.20	0.12	0.01	0.004
Arco, PA	6.54	4.03	2.12	1.20	0.65	0.38	0.04	0.01
Arco, TX	25.2	15.5	8.15	4.60	2.50	1.45	0.15	0.04
Cos-Mar	1.43	4.10	4.22	3.48	2.16	1.37	0.17	0.05
Dow, TX	15.1	9.30	4.89	2.76	1.50	0.87	0.09	0.03
Dow, MI	6.04	3.72	1.96	1.10	0.60	0.35	0.04	0.01
El Paso	0.04	0.13	0.13	0.11	0.07	0.04	0.005	0.001
Gulf	0.59	1.70	1.76	1.45	0.90	0.57	0.07	0.02
Monsanto	0.002	0.030	0.068	0.082	0.076	0.058	0.010	0.004
Oxirane	0.99	2.84	2.93	2.41	1.49	0.95	0.12	0.03
Sun Oil	1.51	0.93	0.49	0.28	0.15	0.09	0.009	0.003
U.S. Steel	0.00001	0.00015	0.00034	0.00041	0.00038	0.00029	0.00005	0.00002

TABLE E-5. SCALED MEAN ANNUAL AVERAGE BENZENE CONCENTRATIONS IN PARTS PER BILLION (ppb) AT DISTANCE FROM PLANT IN KILOMETERS (km) FUGITIVE AND STORAGE CONTRIBUTION[a]

PLANT	DISTANCE (km)							
	0.16-0.3	0.3-0.5	0.5-0.7	0.7-1.0	1.0-1.5	1.5-2.0	2.0-10.0	10.0-20.0
Am. Hoechst	11.3	6.02	3.20	1.79	0.96	0.55	0.06	0.02
Amoco	8.46	4.51	2.40	1.34	0.72	0.41	0.05	0.02
Arco, PA	1.41	0.75	0.40	0.22	0.12	0.07	0.008	0.003
Arco, TX	4.94	2.63	1.40	0.78	0.42	0.24	0.03	0.01
Cos-Mar	14.1	7.52	4.00	2.24	1.20	0.68	0.08	0.03
Dow, TX	16.2	8.65	4.60	2.58	1.38	0.79	0.09	0.03
Dow, MI	0.71	0.38	0.20	0.11	0.06	0.03	0.004	0.001
El Paso	3.24	1.73	0.92	0.52	0.28	0.16	0.02	0.007
Gulf	6.35	3.38	1.80	1.01	0.54	0.31	0.03	0.01
Monsanto	14.1	7.52	4.00	2.24	1.20	0.68	0.08	0.03
Oxirane	10.6	5.64	3.00	1.68	0.90	0.51	0.06	0.02
Sun Oil	2.12	1.13	0.60	0.34	0.18	0.10	0.01	0.004
U.S. Steel	0.71	0.38	0.20	0.11	0.06	0.03	0.004	0.001

[a] Fugitive emission sources are assumed uncontrolled. Storage tank emission sources are partially controlled and reflect current levels of benzene control.

TABLE E-6. SCALED MEAN ANNUAL AVERAGE BENZENE CONCENTRATIONS IN PARTS PER BILLION (ppb) AT DISTANCE FROM PLANT IN KILOMETERS (km) PROCESS, FUGITIVE, AND STORAGE EMISSIONS

PLANT	DISTANCE (km)							
	0.16-0.3	0.3-0.5	0.5-0.7	0.7-1.0	1.0-1.5	1.5-2.0	2.0-10.0	10.0-20.0
Am. Hoechst	41.5	24.6	13.0	7.31	3.96	2.29	0.24	0.08
Amoco	10.5	5.75	3.05	1.71	0.92	0.53	0.06	0.02
Arco, PA	7.95	4.78	2.52	1.42	0.77	0.45	0.05	0.01
Arco, TX	30.1	18.1	9.55	5.38	2.92	1.69	0.18	0.05
Cos-Mar	15.5	11.6	8.23	5.72	3.36	2.05	0.25	0.07
Dow, TX	31.3	18.0	9.49	5.34	2.88	1.66	0.18	0.06
Dow, MI	6.74	4.10	2.16	1.22	0.66	0.38	0.04	0.01
El Paso	3.29	1.86	1.05	0.62	0.34	0.20	0.02	0.008
Gulf	6.94	5.09	3.56	2.46	1.44	0.87	0.10	0.03
Monsanto	14.1	7.55	4.07	2.32	1.28	0.74	0.09	0.03
Oxirane	11.6	8.48	5.93	4.09	2.39	1.46	0.17	0.05
Sun Oil	3.62	2.06	1.09	0.61	0.33	0.19	0.02	0.007
U.S. Steel	0.71	0.38	0.20	0.11	0.06	0.03	0.004	0.001

TABLE E-7. SCALED MEAN ANNUAL AVERAGE BENZENE CONCENTRATIONS IN PARTS PER BILLION (ppb) AT DISTANCE FROM PLANT IN KILOMETERS (km) EXCESS EMISSIONS CONTRIBUTION UNCONTROLLED LEVEL ASSUMED[a]

PLANT	DISTANCE (km)							
	0.16-0.3	0.3-0.5	0.5-0.7	0.7-1.0	1.0-1.5	1.5-2.0	2.0-10.0	10.0-20.0
Am. Hoechst	1.40	0.09	0.05	0.03	0.02	0.01	0.0009	0.0004
Amoco	1.97	1.29	0.74	0.44	0.26	0.15	0.01	0.005
Arco, PA	0.87	0.57	0.33	0.20	0.11	0.07	0.006	0.002
Arco, TX	0.22	0.14	0.08	0.05	0.03	0.02	0.002	0.0006
Cos-Mar	3.15	2.07	0.18	0.71	0.41	0.24	0.022	0.0081
Dow, TX	0.51	0.33	0.19	0.11	0.07	0.04	0.003	0.001
Dow, MI	0.78	0.51	0.29	0.18	0.10	0.06	0.005	0.002
El Paso	0.61	0.40	0.23	0.14	0.08	0.05	0.004	0.002
Gulf	1.46	0.96	0.55	0.33	0.19	0.11	0.01	0.004
Monsanto	3.63	2.38	1.36	0.82	0.48	0.27	0.02	0.009
Oxirane	2.42	1.59	0.91	0.54	0.32	0.18	0.02	0.006
Sun Oil	0.16	0.10	0.06	0.04	0.02	0.01	0.001	0.005
U.S. Steel	0.29	0.19	0.11	0.06	0.04	0.02	0.002	0.0007

[a] Since actual equipment and respective control efficiencies for excess emissions are unknown, completely uncontrolled conditions are assumed. This assumption may, in some cases, result in overstatement of prevailing benzene concentrations for excess emissions.

TABLE E-8. BENZENE EXPOSURE IN THOUSANDS OF PPB PERSON-YEARS

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage	Excess Emissions	Combined
Am. Hoechst	101.0	34.1	0.558	136
Amoco	5.18	19.6	6.09	30.9
Arco, PA	16.9	3.33	2.69	22.9
Arco, TX	16.1	2.94	0.168	19.2
Cos-Mar	5.51	3.55	1.03	10.1
Dow, TX	7.80	7.61	0.313	15.7
Dow, MI	12.4	1.29	1.90	15.6
El Paso	0.42	1.45	0.346	2.22
Gulf	1.06	0.65	0.190	1.90
Monsanto	1.74	32.7	11.2	45.6
Oxirane	18.9	11.6	3.4	33.9
Sun Oil	2.76	3.55	0.341	6.66
U.S. Steel	0.340	3.06	1.60	5.00

TABLE E-9. DEATHS PER YEAR, CURRENT CONTROL LEVELS

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage	Excess Emissions	Combined
Am. Hoechst	3.4×10^{-2}	1.2×10^{-2}	1.9×10^{-4}	4.6×10^{-2}
Amoco	1.8×10^{-3}	6.7×10^{-3}	2.1×10^{-3}	1.1×10^{-2}
Arco, PA	5.7×10^{-3}	1.1×10^{-3}	9.2×10^{-4}	7.8×10^{-3}
Arco, TX	5.5×10^{-3}	1.0×10^{-4}	5.7×10^{-5}	5.6×10^{-3}
Cos-Mar	1.9×10^{-3}	1.2×10^{-3}	3.5×10^{-4}	3.3×10^{-3}
Dow, TX	2.7×10^{-3}	2.6×10^{-3}	1.1×10^{-4}	5.3×10^{-3}
Dow, MI	4.2×10^{-3}	4.4×10^{-4}	6.5×10^{-4}	5.3×10^{-3}
El Paso	1.4×10^{-4}	4.9×10^{-4}	1.2×10^{-4}	7.5×10^{-4}
Gulf	3.6×10^{-4}	2.2×10^{-4}	6.4×10^{-5}	6.5×10^{-4}
Monsanto	5.9×10^{-4}	1.1×10^{-2}	3.8×10^{-3}	1.5×10^{-2}
Oxirane	6.4×10^{-3}	3.9×10^{-3}	1.1×10^{-3}	1.1×10^{-2}
Sun Oil	9.4×10^{-4}	1.2×10^{-3}	1.2×10^{-4}	2.3×10^{-3}
U.S. Steel	1.2×10^{-4}	1.0×10^{-3}	5.4×10^{-4}	1.7×10^{-3}
INDUSTRY TOTAL	6.4×10^{-2}	4.2×10^{-2}	1.0×10^{-2}	1.2×10^{-1}

TABLE E-10. SCALED HIGHEST MAXIMUM ANNUAL AVERAGE BENZENE CONCENTRATIONS IN PARTS PER BILLION (ppb)[a]

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage[b]	Excess Emissions[b]	Combined
Am. Hoechst	63.6[b]	32.0	6.09	102
Amoco	4.20[b]	24.1	4.42	32.7
Arco, PA	13.8[b]	4.01	2.33	20.1
Arco, TX	53.0[b]	14.0	2.64	69.6
Cos-Mar	9.0[c] (0.5 @ 0.16 km)	40.1	3.38	44.0
Dow, TX	31.8[b]	46.1	7.90	85.8
Dow, MI	12.7[b]	2.01	2.09	16.8
El Paso	0.28[c] (0.016 @ 0.16 km)	9.20	1.32	10.5
Gulf	3.70[c] (0.22 @ 0.16 km)	18.1	3.17	21.5
Monsanto	0.19[d] (0.0003 @ 0.16 km)	40.1	7.90	48.0

TABLE E-10 (Cont'd)

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage[b]	Excess Emissions[b]	Combined
Oxirane	6.20[c] (0.37 @ 0.16 km)	30.1	5.25	35.7
Sun Oil	3.20[b]	6.02	0.42	9.64
U.S. Steel	0.00095[b] (0.0000015 @ 0.16 km)	2.01	0.63	2.64

[a] Scaled process benzene concentrations for Options A, B, and C are maximum at 0.5, 1.0, and 1.0 km, respectively. Excess benzene emissions for Options 1 and 2 both reached a maximum benzene concentration at a distance of 2.0 km. When the health impact from one of the above single sources is examined, the concentration at the stated distance is used in the calculation. In order to determine the health impact of two or more combined sources, the location (both ring distance and receptor point) of the more significant concentration is recorded and the concentration of the less significant contributor is noted at that same location. This methodology is not apparent for the current controls condition since nearly all benzene concentrations from all sources are maximum at 0.16 km from the plant.

[b] Highest maximum annual average benzene concentration occurs at 0.16 km downwind of plant.

[c] Highest maximum annual average concentration occurs at 0.5 km; value in parentheses is process vent contribution for combined emissions at 0.16 km from plant.

[d] Highest maximum annual average concentration occurs at 1.0 km; value in parentheses is process vent contribution for combined emissions at 0.16 km from plant.

TABLE E-11. MAXIMUM LIFETIME RISK[a]

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage	Excess Emissions	Combined
Am. Hoechst	1.5×10^{-3}	7.6×10^{-4}	1.4×10^{-4}	2.4×10^{-3}
Amoco	1.0×10^{-4}	5.7×10^{-4}	1.1×10^{-4}	7.8×10^{-4}
Arco, PA	3.3×10^{-4}	9.5×10^{-5}	5.5×10^{-5}	4.8×10^{-4}
Arco, TX	1.3×10^{-3}	3.3×10^{-4}	6.3×10^{-5}	1.7×10^{-3}
Cos-Mar	1.2×10^{-5}	9.5×10^{-4}	8.0×10^{-5}	9.7×10^{-4}
Dow, TX	7.6×10^{-4}	1.1×10^{-3}	1.9×10^{-4}	2.1×10^{-3}
Dow, MI	3.0×10^{-4}	4.8×10^{-5}	5.0×10^{-5}	4.0×10^{-4}
El Paso	3.8×10^{-7}	2.2×10^{-4}	3.1×10^{-5}	2.5×10^{-4}
Gulf	5.2×10^{-6}	4.3×10^{-4}	7.5×10^{-5}	5.1×10^{-4}
Monsanto	7.1×10^{-9}	9.5×10^{-4}	1.9×10^{-4}	1.1×10^{-3}
Oxirane	8.8×10^{-6}	7.2×10^{-4}	1.2×10^{-4}	8.5×10^{-4}
Sun Oil	7.6×10^{-5}	1.4×10^{-4}	1.0×10^{-5}	2.3×10^{-4}
U.S. Steel	3.6×10^{-11}	4.8×10^{-5}	1.5×10^{-5}	6.3×10^{-5}

[a] See footnote (a) on Table E-10.

TABLE E-12. DEATHS PER YEAR EXPRESSED AS A 95 PERCENT CONFIDENCE INTERVAL

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage	Excess Emissions	Combined
Am. Hoechst	1.3×10^{-2} - 9.0×10^{-2}	4.4×10^{-3} - 3.1×10^{-2}	7.2×10^{-5} - 5.0×10^{-4}	1.7×10^{-2} - 1.2×10^{-1}
Amoco	6.8×10^{-4} - 4.8×10^{-3}	2.5×10^{-3} - 1.8×10^{-2}	7.8×10^{-4} - 5.5×10^{-3}	4.0×10^{-3} - 2.8×10^{-2}
Arco, PA	2.2×10^{-3} - 1.5×10^{-2}	4.3×10^{-4} - 3.0×10^{-3}	3.5×10^{-4} - 2.4×10^{-3}	3.0×10^{-3} - 2.0×10^{-2}
Arco, TX	2.1×10^{-3} - 1.4×10^{-2}	3.8×10^{-4} - 2.6×10^{-3}	2.2×10^{-5} - 1.5×10^{-4}	2.5×10^{-3} - 1.7×10^{-2}
Cos-Mar	7.1×10^{-4} - 5.0×10^{-3}	4.6×10^{-4} - 3.2×10^{-3}	1.3×10^{-4} - 9.2×10^{-4}	1.3×10^{-3} - 8.7×10^{-3}
Dow, TX	1.0×10^{-3} - 7.0×10^{-3}	9.8×10^{-4} - 6.8×10^{-3}	4.0×10^{-5} - 2.8×10^{-4}	2.0×10^{-3} - 1.4×10^{-2}
Dow, MI	1.6×10^{-3} - 1.1×10^{-2}	1.7×10^{-4} - 1.2×10^{-3}	2.4×10^{-4} - 1.7×10^{-3}	2.0×10^{-3} - 1.4×10^{-2}
El Paso	5.4×10^{-5} - 3.7×10^{-4}	1.9×10^{-4} - 1.3×10^{-3}	4.5×10^{-5} - 3.1×10^{-4}	2.8×10^{-4} - 2.0×10^{-3}
Gulf	1.4×10^{-4} - 9.5×10^{-4}	8.4×10^{-5} - 5.9×10^{-4}	2.4×10^{-5} - 1.7×10^{-4}	2.5×10^{-4} - 1.7×10^{-3}
Monsanto	2.2×10^{-4} - 1.5×10^{-3}	4.2×10^{-3} - 2.9×10^{-2}	1.4×10^{-3} - 1.0×10^{-2}	5.7×10^{-3} - 4.0×10^{-2}
Oxirane	2.4×10^{-3} - 1.7×10^{-2}	1.5×10^{-3} - 1.0×10^{-2}	4.3×10^{-4} - 3.0×10^{-3}	4.3×10^{-3} - 3.0×10^{-2}
Sun Oil	3.6×10^{-4} - 2.5×10^{-3}	4.6×10^{-4} - 3.2×10^{-3}	4.4×10^{-5} - 3.1×10^{-4}	8.6×10^{-4} - 6.0×10^{-3}
U.S. Steel	4.5×10^{-5} - 3.2×10^{-4}	3.9×10^{-4} - 2.7×10^{-3}	2.1×10^{-4} - 1.4×10^{-3}	6.1×10^{-4} - 4.2×10^{-3}
INDUSTRY TOTAL	2.4×10^{-2} - 1.7×10^{-1}	1.7×10^{-2} - 1.1×10^{-1}	3.3×10^{-3} - 2.6×10^{-2}	4.0×10^{-2} - 3.1×10^{-1}

TABLE E-13. MAXIMUM LIFETIME RISK EXPRESSED AS A 95 PERCENT CONFIDENCE INTERVAL[a]

PLANT	EMISSION SOURCE			
	Continuous Emissions			
	Process	Fugitive and Storage	Excess Emissions	Combined
Am. Hoechst	$5.7 \times 10^{-4} - 4.0 \times 10^{-3}$	$2.9 \times 10^{-4} - 2.0 \times 10^{-3}$	$5.3 \times 10^{-5} - 3.7 \times 10^{-4}$	$9.1 \times 10^{-4} - 6.3 \times 10^{-3}$
Amoco	$3.8 \times 10^{-5} - 2.6 \times 10^{-4}$	$2.2 \times 10^{-4} - 1.5 \times 10^{-3}$	$4.2 \times 10^{-5} - 2.9 \times 10^{-4}$	$3.0 \times 10^{-4} - 2.1 \times 10^{-3}$
Arco, PA	$1.2 \times 10^{-4} - 8.7 \times 10^{-4}$	$3.6 \times 10^{-5} - 2.5 \times 10^{-4}$	$2.1 \times 10^{-5} - 1.5 \times 10^{-4}$	$1.8 \times 10^{-4} - 1.3 \times 10^{-3}$
Arco, TX	$4.9 \times 10^{-4} - 3.4 \times 10^{-3}$	$1.2 \times 10^{-4} - 8.7 \times 10^{-4}$	$2.4 \times 10^{-5} - 1.7 \times 10^{-4}$	$6.4 \times 10^{-4} - 4.5 \times 10^{-3}$
Cos-Mar	$4.5 \times 10^{-6} - 3.2 \times 10^{-5}$	$3.6 \times 10^{-4} - 2.5 \times 10^{-3}$	$3.0 \times 10^{-5} - 2.1 \times 10^{-4}$	$3.6 \times 10^{-4} - 2.5 \times 10^{-3}$
Dow, TX	$2.9 \times 10^{-4} - 2.0 \times 10^{-3}$	$4.2 \times 10^{-4} - 2.9 \times 10^{-3}$	$7.2 \times 10^{-5} - 5.0 \times 10^{-4}$	$7.9 \times 10^{-4} - 5.5 \times 10^{-3}$
Dow, MI	$1.1 \times 10^{-4} - 7.9 \times 10^{-4}$	$1.8 \times 10^{-5} - 1.3 \times 10^{-4}$	$1.9 \times 10^{-5} - 1.3 \times 10^{-4}$	$1.5 \times 10^{-4} - 1.1 \times 10^{-3}$
El Paso	$1.4 \times 10^{-7} - 1.0 \times 10^{-6}$	$8.3 \times 10^{-5} - 5.8 \times 10^{-4}$	$1.2 \times 10^{-5} - 8.2 \times 10^{-5}$	$9.5 \times 10^{-5} - 6.6 \times 10^{-4}$
Gulf	$2.0 \times 10^{-6} - 1.4 \times 10^{-5}$	$3.3 \times 10^{-4} - 1.1 \times 10^{-3}$	$2.8 \times 10^{-5} - 2.0 \times 10^{-4}$	$1.9 \times 10^{-4} - 1.3 \times 10^{-3}$
Monsanto	$2.7 \times 10^{-9} - 1.8 \times 10^{-8}$	$3.6 \times 10^{-4} - 2.5 \times 10^{-3}$	$7.2 \times 10^{-5} - 5.0 \times 10^{-4}$	$4.3 \times 10^{-4} - 3.0 \times 10^{-3}$
Oxirane	$3.3 \times 10^{-6} - 2.3 \times 10^{-5}$	$2.7 \times 10^{-4} - 1.9 \times 10^{-3}$	$4.5 \times 10^{-5} - 3.2 \times 10^{-4}$	$3.2 \times 10^{-4} - 2.2 \times 10^{-3}$
Sun Oil	$2.9 \times 10^{-5} - 2.0 \times 10^{-4}$	$5.3 \times 10^{-5} - 3.7 \times 10^{-4}$	$3.8 \times 10^{-6} - 2.6 \times 10^{-5}$	$8.7 \times 10^{-5} - 6.1 \times 10^{-4}$
U.S. Steel	$1.4 \times 10^{-11} - 9.5 \times 10^{-11}$	$1.8 \times 10^{-5} - 1.3 \times 10^{-4}$	$5.7 \times 10^{-6} - 4.0 \times 10^{-5}$	$2.4 \times 10^{-5} - 1.7 \times 10^{-4}$

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[a] See footnote (a) on Table E-10.

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4. Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1977. American Conference of Governmental Industrial Hygienists. 1977.

5. Revised Recommendation for an Occupational Exposure Standard for Benzene. National Institute for Occupational Safety and Health. August 1976.

6. Occupational Safety and Health Standards, 29 CFR 1910.1000, Table 7-2. Occupational Safety and Health Administration Publication OSHA 2206. 1976.

7. A benzene standard with a limit of one ppm was proposed by OSHA May 27, 1977 (42 FR 27452) and promulgated February 10, 1978 (43 FR 5918). This standard was struck down October 5, 1978 by the U.S. Fifth Circuit Court of Appeals. The U.S. Department of Labor appealed the decision and the Supreme Court agreed to hear arguments on the case during its Fall 1979 term. A decision is unlikely before early 1980.

8. 42 FR 27452. May 27, 1977.

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AA. ADDENDUM

BACKGROUND INFORMATION FOR PROPOSED STANDARDS FOR BENZENE EMISSIONS FROM THE ETHYLBENZENE/STYRENE INDUSTRY

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1. ENFORCEMENT ASPECTS

1.1 INTRODUCTION

The proposed standard for the ethylbenzene/styrene (EB/S) industry would limit benzene emissions from process vents at existing and new EB/S plants to five parts per million by volume (ppmv). Emissions in excess of this numerical emissions limit would be allowed only during startup, shutdown, and malfunctions. During these times, however, these emissions would have to be flared. This addendum outlines sections of the standard of potential concern to enforcement personnel. Areas examined include: the applicability of the proposed standard to EB/S processes and vent streams, the routing of vent streams, excess emissions, and monitoring methods.

1.2 EB/S PROCESSES AND VENT STREAMS

The two processes used domestically to produce ethylbenzene are benzene alkylation with ethylene and mixed xylene extraction. The two processes used to produce styrene are ethylbenzene dehydrogenation and ethylbenzene hydroperoxidation. The proposed standard would apply to each plant which produces ethylbenzene from benzene alkylation or which produces styrene from ethylbenzene dehydrogenation or ethylbenzene hydroperoxidation. Plants producing ethylbenzene from mixed xylenes are not regulated under this standard.

The following benzene-containing streams from the three covered processes would be regulated under the proposed standard:

- Alkylation reactor section vents
- Atmospheric or pressure column vents
- Vacuum-producing device vents
- Hydrogen separation system vents.

The alkylation section in the typical EB/S plant will have two to four vents. In general, one of these vents will be on the alkylation reactor itself and the others on catalyst neutralization separation vessels immediately downstream of the reactor. The distillation column area typically will have six to ten vents. In general, there will be one vent on each vacuum atmosphere and pressure column. The vent streams in the alkylation reactor section and column area have low flows, generally less than 100 standard cubic feet per minute (scfm). The vents may be piped together and released at a common point.

The hydrogen separation system typically will have only one vent stream. Since this stream has a high flow and Btu value, most plants use this stream as fuel.

The definition of process vent in the proposed standard is written so that certain vents in an EB/S unit are not covered. These vents are not covered since they either have negligible benzene emissions or are to be covered under other standards. The vents not covered may include, at a typical EB/S plant, catalyst preparation area vents, intermediate product storage vents, and compressor lube oil vents, among others.

The typical EB/S plant produces ethylbenzene by benzene alkylation and styrene by ethylbenzene dehydrogenation. However, depending upon process variations and plant capacity, the production train and the number of vents at each plant may vary. For example, one plant produces styrene by ethylbenzene hydroperoxidation and some plants produce only ethylbenzene or only styrene. Plants which produce only ethylbenzene will not have a hydrogen separation section vent and plants which produce only styrene will not have alkylation reactor section vents. Consequently, it is important for enforcement personnel to be cognizant of these variations in reviewing monitoring records and during plant inspections.

1.3 ROUTING OF THE VENT STREAMS

In controlling continuous process benzene vent streams, plant operators will route these streams to a control device. Generally, a boiler* will be used to meet the numerical emissions limit. However, EB/S plant operators are not restricted to the use of boilers and can use any control device which meets the requirements of the regulation.

Because of the number of vent streams to be controlled and the complexity of EB/S plants, the routing of the process vent streams to the control device may be equally complex. In addition, in some cases, smaller process vent streams covered by the standard can be vented to the atmosphere without a noticeable change in the flow entering a control device or compressor. Therefore, special attention should be given to determine if the proper streams are being routed to each control device. During plant inspections, enforcement personnel should request a process flow sheet detailing all the process vent streams to be controlled, all relevant control valves, and the control devices. A process description and a flow diagram of the specific process, along with the generalized descriptions and diagrams in the Background Information Document, should help verify proper routing.

1.4 EXCESS EMISSIONS

Emissions in excess of the numerical emissions limit would be allowed only during startup, shutdown, and malfunctions. During these times, however, these emissions would have to be flared. Particular attention, therefore, should be given to the definition of these periods of permissible excess emissions.

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*The term "boiler" includes process heaters and superheaters.

Startup involves bringing into full operation all equipment in the entire plant, the dehydrogenation section, or the alkylation reactor section, which is originally at ambient temperature and empty of process liquids. Conversely, a shutdown involves terminating operation of either all equipment in the entire plant, the dehydrogenation section, or the alkylation reactor section, and allowing the equipment to cool to ambient temperature. Complete plant startup and shutdown each generally require 12 to 24 hours and occur on an average of once every two years. The emissions from startup and shutdown occur because the volume of the hydrogen offgas stream is below the minimum needed for the hydrogen separation compressor(s) to operate and therefore cannot be sent to the boiler. The stream therefore would have to be vented to the flare.

The only other time during which the five ppmv emissions limit can be exceeded is during periods of malfunction. During malfunctions, the benzene-containing vent streams would have to be combusted in a flare. Process and control device failures occur periodically; compressor outages are the most common process failures. Process or control equipment failures that are sudden and unavoidable are by definition malfunctions. Conversely, process or control equipment failures caused entirely or in part as a result of design deficiencies, poor maintenance, careless operation, or other preventable equipment breakdown would not be considered malfunctions. Although specific criteria on which this decision is based are not definitive, certain indicators, such as frequency of breakdown, age of equipment, and the sequence of events leading to the equipment failure, should provide supportive information for enforcement personnel to determine whether or not a preventable equipment breakdown occurred.

Enforcement personnel should pay particular attention to failures of equipment which is not central to the operation of the process. For example, the hydrogen separation compressor must be kept in good operating condition for the process to operate economically. The other vent compressors, however, are not central to the process operation. Malfunctions of these compressors may go unrepaired for long periods of time. Excessive delays in repairing these compressors would constitute a violation of the standard. Enforcement personnel therefore should obtain a complete description of the equipment causing the malfunction and the reason for the malfunction. This information, along with a knowledge of the relative importance of the equipment to the process, should allow enforcement personnel to determine the validity of a claim of malfunction.

1.5 MONITORING

The final potential area of concern to enforcement personnel is emission monitoring and testing. Because the standard is based on known benzene destruction of 99 percent in a boiler, a quantitative benzene monitor which would measure the benzene emissions exiting a control device, such as a gas chromatograph monitor, is unnecessary. An equally effective approach directly applicable to boilers involves installation of a firebox temperature monitor and flue gas oxygen monitors, each equipped with a strip chart recorder, which measures and records critical operating parameters of the boiler. If these monitors indicate that the control device is operating within the range specified in the proposed rule, benzene emissions from the boiler stack should be in compliance with the standard.

An additional continuous monitoring device, flow meters coupled to a strip chart recorder, would determine if all benzene-containing streams are ducted from the compressors to the control device. These would be placed at strategic points on the piping and would indicate if any benzene-containing streams are diverted from the boiler.

To further check that benzene-containing streams are routed properly to the boiler, the proposed standard requires weekly visual checks of vent stream piping, valves, compressors, and other components. These checks include components not on ground levels and the operator, therefore, may need to climb to inspect some components. Operators are to keep logs of their inspections and are to report improper routings if they occur more than once every 90 days.

For plants which use control devices other than boilers, monitoring would be done by gas chromatography with a flame ionization detector.

Monitoring devices, in addition to periodic visual checks on valve positions, will provide sufficient information for determining compliance with the standard. All monitoring equipment should be in operation before the emission tests. Enforcement personnel should visually check during the test to determine if all vents covered by the standard are being routed to the control device.

2. REPORTS IMPACT ANALYSIS

2.1 LEGAL AUTHORITY

Under the authority of §112(b)(1) of the Clean Air Act, as amended, the Environmental Protection Agency (EPA) proposes a national emission standard for benzene emissions from ethylbenzene/styrene (EB/S) plants. Under §114(a) of the Act, the Administrator may require any owner or operator of an EB/S plant to "(A) establish and maintain such record, (B) make such reports, (C) install, use, and maintain such monitoring equipment or methods, (D) sample such emissions (in accordance with such methods, at such locations, at such intervals, and in such manner as the Administrator shall prescribe), and (E) provide such other information, as he may reasonably require."

2.2 BACKGROUND

2.2.1 Purpose

Sections 61.102(a) and (b) of the proposed standard require that owners or operators of EB/S plants limit to five parts per million the amount of benzene being discharged to the atmosphere from a process vent stream(s) and combust unavoidable excess emissions due to startup, shutdown, and malfunction by one or more smokeless flares at all times. Section 61.102(c) requires that each owner or operator maintain each source, including associated air pollution equipment, in a manner consistent with good air pollution control practices for minimizing benzene emissions. To determine whether an owner or operator is in compliance with the standard, and to determine whether acceptable operating and maintenance procedures are being used, the

Administrator needs specific information concerning plant operations, maintenance, and monitoring procedures.

2.2.2 Narrative Description

The proposed standard requires that specific information concerning emissions in excess of the standard be reported to the Administrator within ten days of each incidence of the excess. This includes the identity of the process vent stream where the excess occurs, continuous monitoring and operational data which indicate the excess emissions, the cause and description of the excess emissions, the duration of the excess emissions, and whether the owner or operator believes that the excess emissions were due to startup, shutdown, or malfunction. If the owner or operator states that he or she believes that the excess emissions were during startup, shutdown, or malfunction, he or she must include the steps taken to remedy and prevent a recurrence of the malfunction and documentation that good engineering practices were followed. Owners or operators of sources which use boilers* as the air pollution control device also must keep daily records of the oxygen level as determined by the flue gas oxygen monitor, the firebox temperature as determined by the firebox monitor, the flow level as measured by the compressor flow meter, visual checks to determine if the process vent streams were going to the control device, and emission test results. Owners or operators of sources which use air pollution control devices other than boilers must keep daily records of the concentration of benzene measured in the exhaust gas by the monitor specified in §61.105, the flow level as measured by the compressor flow meter, visual checks to determine if the process vent streams are going to the control device, and other data needed to determine emissions as specified in §61.104. The Administrator has not requested a specific format for the information required to be submitted or kept in daily records.

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*Boilers include process heaters, superheaters, and other similar units.

These requirements apply to the owners and operators of 13 plants which produce ethylbenzene, styrene, or both. Of these 13 plants, 12 produce styrene, 11 produce ethylbenzene, and nine are integrated plants producing ethylbenzene/styrene. A recent analysis of the EB/S industry revealed that no new plants are expected to be constructed within the next five years.

2.3 ALTERNATIVES

To ensure that the requirements of this standard minimize the public reporting and recordkeeping burden while maximizing EPA program effectiveness, the Administrator considered alternatives to the recordkeeping, reporting, and continuous monitoring requirements discussed above.

One alternative that he considered, for sources which use air pollution control devices other than boilers, was not to require that records be kept of the benzene concentration and amount of excess oxygen in the exhaust gas, or that the records be kept, but not on a daily basis. In control devices such as boilers (BAT), there is potential for air dilution. These devices use excess air to aid combustion and the quantity of excess air can vary. This information therefore is needed on a daily basis to ensure that each EB/S plant is in compliance with the standard and that the quantity of benzene emitted is the same regardless of how much excess air is used. For sources which use boilers, the Administrator considered not requiring all the monitoring data be recorded and kept. However, many EB/S plants currently keep records of this information and it therefore would not impact the EB/S industry's recordkeeping practices.

The Administrator also considered further limiting the amount of information reported during incidences of excess emissions. The standard requires that good air pollution control be practiced for limiting benzene emissions. To ensure that plants are practicing good air pollution control, the Administrator determined that these data were necessary.

Intermittent monitoring was considered as an alternative to continuous monitoring. Both types of monitoring require the same equipment, maintenance, and operating procedures. Intermittent monitoring would not require as extensive manpower requirements, but would not provide as effective means of ensuring compliance as continuous monitoring. Given this, the Administrator determined that continuous monitoring was the best means of maximizing EPA program effectiveness while minimizing monitoring burdens.

2.4 IMPACT ANALYSIS

2.4.1 Respondent Labor Requirements

Table 2-1 represents the labor requirements for the EB/S industry to comply with the recordkeeping, reporting, and monitoring requirements of the proposed standard. Because no new EB/S plants are expected to be constructed within the next five years, these requirements are only for existing sources. The labor requirements are estimates through the fifth year of applicability of the standard.

2.4.2 Agency Labor Requirements

Table 2-2 details the labor requirements for EPA to fulfill the reporting requirements of the standard. The labor requirements are estimates through the fifth year of applicability of the standard.

TABLE 2-1. LABOR REQUIREMENTS TO FULFILL THE RECORDKEEPING, REPORTING, AND MONITORING REQUIREMENTS OF THE PROPOSED STANDARD

Requirements	Employee Hours Per Report	Number Of Sources	Total Employee Hrs
NESHAP Compliance Status Information Report	2	13	26
Waiver Application	2	0	0
Notification of Physical or Operational Changes	1	0	0
Notification of Demonstration of the Continuous Monitoring System	1	13	91
Continuous Monitoring Demonstration Report	8	13	1,300
Excess Emissions Reports	20	13	2,600
Recordkeeping Requirements	40	13	2,600
Notification of the Administrator before an Emissions Test	1	13	162.5
Emission Test Reports	8	13	1,300
Notification of the Administrator before Startup	1	13	32.5
TOTAL			8,112

TABLE 2-2. LABOR REQUIREMENTS TO FULFILL THE REPORTING REQUIREMENTS OF THE PROPOSED STANDARD

Requirements	Employee Hours Per Report	Number Of Reports	Total Employee Hrs
Review NESHAP Compliance Status Information Report	2	13	26
Review Waiver Application	2	0	0
Review Notification of Physical or Operational Changes	1	0	0
Review Notification of Demonstration of the Continuous Monitoring System	1	13	13
Review Continuous Monitoring Demonstration Report	8	162.5	1,300
Review Excess Emissions Report	4 8	130 6.5	572
Review Notification of the Administrator before Emission Test	1	162.5	162.5
Review Emission Test Reports	4	162.5	650
Review of Notification of Startup	1	32.5	32.5
TOTAL			2,756

3. EXCESS EMISSIONS

3.1 INTRODUCTION

Existing data indicate that emissions in excess of the numerical emissions limit are unavoidable during startup, shutdown, and some equipment failures at EB/S plants. Some emissions are due to sudden and unavoidable equipment failures and are by definition malfunctions. Others, however, are a result of deficiencies in design, poor maintenance, or careless operation and are by definition avoidable. Because unavoidable emissions occurring during startup, shutdown, and malfunction could exceed the numerical emissions limit for EB/S plants, plant owners or operators would not be in compliance with the standard which requires that good air pollution control practice be followed and would be subject to enforcement procedures. The Administrator therefore has considered alternative regulatory options for regulating unavoidable excess emissions.

3.2 PROCESSES AND THEIR EMISSIONS

Unavoidable excess emissions can occur during (1) startup, (2) shutdown, and (3) as a result of either process or air pollution control equipment malfunction.

3.2.1 Startup

Startup involves bringing to full operation equipment in either the entire plant, the alkylation reaction section, or the dehydrogenation section, which is originally at ambient temperature and empty of process liquids. Plant startup occurs on the average of once every two years and involves gradually bringing all empty and non-operating equipment, initially at ambient temperature, to full operating temperatures. The procedure requires an average of approximately 12 to 24 hours to fully establish reactions and ensure that the quality of the product meets specifications. In this interim period, however, benzene emissions in excess of the standard can be released from certain points in the production train.

The benzene emission potential during one startup period is approximately 4,200 kg/yr for ten hours per year from the entire 300,000 Mg/yr uncontrolled model plant, most of which is from the hydrogen separation vent. Due to a lack of sufficient flow during startup, this stream is not compressed and sent to the aromatic recovery section as is the case during normal production. Rather, typical practice involves either venting the stream directly to the atmosphere, recycling the stream, or flaring it until the dehydrogenation reaction is established fully. Only after the reaction is established and the volume of the stream is sufficient can the gas be compressed, ducted to the aromatic recovery section where the benzene and other condensables are recovered, and the remainder of the stream, largely hydrogen, be sent to the steam superheater for use as supplemental fuel.

3.2.2 Shutdown

Shutdown involves terminating operation of either all equipment in the entire plant, the alkylation reaction section, or the dehydrogenation section and allowing the equipment to cool to ambient temperature. Plant shutdown is necessary an average of once every two years so that equipment can be inspected, cleaned, or replaced. The shutdown procedure for a plant comparable to the 300,000 Mg/yr model plant normally requires about 12 to 24 hours. Actual venting of emissions requires an average of ten hours. The procedure involves cutting off feedstock to the reactors while concurrently decreasing the introduction of steam and catalyst, so that the temperature of all equipment reaches ambient levels. During this procedure, emissions in excess of the standard can occur.

Residual benzene in equipment must be purged before maintenance can begin. During plant shutdown, as in plant startup, the bulk of benzene emissions occur at the hydrogen separation vent. Based on the 300,000 Mg/yr uncontrolled model plant, benzene emissions due to plant shutdown are approximately 4,200 kg/yr from the entire plant.

3.2.3 Equipment Malfunction

Unavoidable excess emissions also occur due to either process or control equipment malfunction. Though benzene emissions due to malfunctions can arise anywhere on the production train, certain pieces of equipment have been cited as likely sources of emissions. Experience has shown that the hydrogen separation compressor is inoperable an average of ten hours per year. The hydrogen separation compressor is necessary for the recovery of aromatics and for producing the necessary pressure to combust the remaining hydrogen-rich stream in the steam superheater. During periods of outage, the benzene-laden stream is either vented directly to the atmosphere or flared. Some plants employ backup compressors which nearly eliminate benzene emissions from this source. In the absence of a backup compressor, the benzene emission potential from this source is approximately 4,000 kg/yr (based on the 300,000 Mg/yr model plant).

Experience has shown a variable potential for benzene emissions in the event of a vent gas compressor outage. Compared to the hydrogen separation compressor, the vent gas compressor services relatively small streams. Its function is to direct gas streams under low or negative pressure to the main header. Since this equipment is not central to styrene production and because the vent streams are small compared to process vent streams, little incentive exists for immediate repair of this equipment. In addition to actual malfunction of this equipment, it is, in many cases, more convenient to turn off the vent gas compressor to avoid more serious or costly operational upsets in other areas of the production train. Records at one plant show that a vent gas compressor had been shut off for months, thereby avoiding more costly repairs. Since the streams directed by this device contain little recoverable product, they usually are vented directly to the atmosphere. Intentional emissions such as these would be considered avoidable and a violation of the standard requiring good air pollution control practices. Assuming plant operators allow the vent gas compressor to remain inoperable for one month, benzene emissions of up to 16,000 kg/yr (for the 300,000 Mg/yr model plant) can occur from the venting of the stream at this source.

3.3 CONTROLS

This section describes applicable control strategies for excess benzene emissions in the EB/S industry and analyzes their efficiencies, advantages, and limitations. The controls discussed are flaring, incineration in an existing boiler, recycling of the vent stream, and backup control devices.

3.3.1 Flaring

Flaring is an important control strategy for limiting excess benzene emissions from the EB/S industry. Various vent streams can be manifolded to a properly-sized flare for thermal destruction. The main advantage of the flare is its ability to control high volume, short duration releases as normally are encountered during equipment malfunction. For example, flares can control emissions due to a hydrogen separation compressor outage, vent gas compressor outage, and streams of highly variable Btu value such as those encountered during startup and shutdown. Chapter 4 of the BID describes flare system equipment and design features. A ten-inch smokeless flare system* is assumed to be used for control of benzene emissions due to malfunction and is essentially identical to the flare system used to control process emissions except for stack diameter and height. Smokeless flares can reduce visible emissions to no more than five minutes or less within a two-hour period. Combustion efficiency for the ten-inch smokeless flare is assumed to be 60 percent.

3.3.2 Boilers

Vent streams can be ducted to the burner of a boiler for thermal destruction of benzene. This control system would use existing EB/S boilers appropriately retrofitted to accept all vent streams. The boiler control system can be retrofitted in two ways. In the first, lower pressure vents first are compressed and then piped along with higher pressure vents into the boiler fuel header and burned with the natural gas fuel. In the second, one or several burners in the boiler are replaced by forced draft burners capable of accepting low pressure streams. The lower pressure vents then are piped to the replacement burners for destruction and higher pressure vents to the fuel header. Forced draft burners are available as standard items for pressures as low as one inch of water gauge.

The chief advantage of this system is its high control efficiency. This is due to the burner's ability to provide excellent fuel/air mixing, relatively long residence time in the flame, and high temperatures. A benzene destruction efficiency of 99 percent is assumed for this analysis.

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*Sized for the 300,000 Mg/yr model plant.

This assumption is based on both engineering analyses and field tests on existing EB/S boilers.

A disadvantage of this system involves the complexity of controls, safety equipment, and manifold design. Due to the variable flow and composition of streams during startup, shutdown, and malfunction, installation of all necessary equipment may be prohibitively expensive.

3.3.3 Recycling of Hydrogen Separation Stream

This method of emission control involves redirecting the hydrogen separation compressor discharge back to its inlet header. This procedure limits benzene emissions by retaining and compressing the stream until conditions are suitable for introduction to a control device. A primary hydrogen separation compressor can be retrofitted to provide recycle capability at minimal cost. Approximately 75 percent of the EB/S industry currently employs this method of control. Its estimated benzene emission reduction potential ranges from 80 to 100 percent.

3.3.4 Backup Hydrogen Separation Compressor

A backup hydrogen separation compressor serves not only to control excess emissions but also allows nearly continuous aromatic recovery. Additionally, it provides nearly continuous utilization of the hydrogen-rich stream after recovery for use as a supplemental fuel. In the event of a primary hydrogen separation compressor outage, the backup compressor is able to come on line within an hour, thereby curtailing potential benzene emissions from the separation vent by 90 to 100 percent.

Though a backup compressor is a fairly costly piece of equipment, it requires no additional energy since only one compressor will be in operation at any one time. Approximately 50 percent of EB/S plants currently employ a backup hydrogen separation compressor. However, for these plants, the second compressor was installed for conditions specific to those plants and these conditions may not exist at other plants.

3.4 REGULATORY OPTIONS

This section discusses the regulatory options applicable to the control of excess benzene emissions resulting from startup and shutdown operations and malfunction. These options are based, in part, on the control devices discussed in Section 3.3. Under each option, avoidable excess emissions due to failures of process or air pollution control equipment caused entirely or in part by deficiencies in design, poor maintenance, careless operation, or other preventable equipment breakdown would not be permitted. Failure of process or control equipment, regardless of the cause, would require prompt repair; failure to do so would constitute avoidable excess emissions.

3.4.1 Baseline Case

A 300,000 Mg/yr, completely uncontrolled model plant is used as a baseline of emissions in assessing the impact of the regulatory options. The extent of emissions from the model plant overstates those currently emitted from existing plants. The sources and assumed baseline emissions of the uncontrolled model plant are as follows:

- The hydrogen separation stream vents to the atmosphere for an average of ten hours per year during startup and ten hours per year during shutdown operations (startup/shutdown operations are assumed to occur once every two years). Total benzene emissions amount to 8,000 kg every two years or 4,000 kg/yr.

- The hydrogen separation stream vents to the atmosphere for an average of ten hours per year during a hydrogen separation compressor outage. Total benzene emissions amount to approximately 4,000 kg/yr.

- The vent gas compressor goes unrepaired or is inoperable for one month, during which time the vent immediately upstream of this device emits 16,000 kg/yr of benzene to the atmosphere.

3.4.2 Regulatory Option 1

Regulatory Option 1 would require that:

- Emissions from startup and shutdown would be flared until the stream can be ducted to the boiler. Assuming a 60 percent benzene destruction efficiency and an average of two hours emission duration, total benzene emissions from this source would be approximately 320 kg/yr.

- All emissions from the hydrogen separation vent due to a hydrogen separation compressor outage would be flared during the entire outage period. Assuming an average ten-hour period, total benzene emissions from this source would be approximately 1,600 kg/yr.

Though not specified as a requirement, Regulatory Option 1 assumes that the following practice is observed:

- The hydrogen separation stream is recycled prior to flaring during startup and shutdown operations, thereby retaining the stream until it can be burned by a smokeless flare.

3.4.3 Regulatory Option 2

Regulatory Option 2 would require that:

- Emissions from startup and shutdown would be flared until the stream can be ducted to the boiler. Assuming a 60 percent benzene destruction efficiency and an average duration of two hours, total benzene emissions from this source would be approximately 320 kg/yr.

- All EB/S plants have a backup hydrogen separation compressor (dual compressor). Additionally, all emissions from the hydrogen separation vent would be flared until the backup compressor is able to come on line. Assuming a 60 percent benzene destruction efficiency, total benzene emissions from this source would be approximately 160 kg/yr.

Though not specified as a requirement, Regulatory Option 2 also assumes that the following practice is observed:

- The hydrogen separation stream is recycled prior to flaring during startup and shutdown operations, thereby retaining the stream until it can be burned by smokeless flares.

3.4.4 Regulatory Option 3

Regulatory Option 3 would require that:

- An existing EB/S boiler would be retrofitted to accept all streams at all times. Assuming a 99 percent benzene destruction efficiency, total emissions from this source would be approximately 80 kg/yr.
- All excess emissions would be flared for short periods required to adjust boiler operation for acceptance of the waste stream at the beginning of an outage. Assuming a 60 percent benzene destruction efficiency, total benzene emissions from this source are approximately 80 kg/yr.

3.4.5 Regulatory Option 4

Regulatory Option 4 (100 percent benzene reduction) requires that:

- All EB/S plants achieve 100 percent benzene reduction. Since this level of emission reduction is not technically feasible, the option assumes plant closure.

3.5 ENVIRONMENTAL AND ENERGY IMPACTS

This section discusses the environmental and energy impacts of the five regulatory options presented in Section 3.4. These options involve limiting benzene emissions from the following sources:

- The hydrogen separation vent during startup and shutdown operations, and hydrogen separation compressor outages.
- Emissions from adjusting the boiler or superheater at the beginning of outages.
- Emissions due to vent gas compressor outages.

3.5.1 Air Impacts

Air quality impacts were analyzed through the use of the Industrial Source Complex (ISC) dispersion model.[1] The methodology used to model excess emissions was the same as that described in Appendix B of the BID, except that only annual average impacts were modeled for excess emissions. Aside from source data, all other impacts and assumptions for the excess emissions modeling are the same as for Appendix B. The estimated total excess benzene emissions for the EB/S industry are 133 Mg/yr under current controls, 21 Mg/yr under Regulatory Option 1, 10 Mg/yr under Regulatory Option 2, and 1 Mg/yr under Regulatory Option 3.

Table 3-1 shows the source impacts used in modeling excess emissions impacts. The 8,000 kg of benzene emissions from process vents under the baseline scenario were divided evenly among the eight process vents for the uncontrolled option.

Table 3-2 presents the results of the excess emissions modeling. For each option, the highest maximum annual average concentration from any plant at any distance is given. The table shows that impacts resulting from Regulatory Options 1, 2, and 3 emissions scenarios are all negligible. Under the baseline scenario, however, excess emissions impacts of up to 7.9 ppb are predicted very near one EB/S plant (0.16 km).

3.5.2 Water Quality Impact and Consumption

None of the regulatory options considered results in any significant increase in wastewater discharge by EB/S facilities. No water effluents are discharged from either flares or boilers. The net water consumption for the boiler is zero. The flares use water in the form of steam which is injected into the combustion zone of the stack. Water consumption for the 300,000 Mg/yr model plant employing a ten-inch flare for excess emissions is negligible.

3.5.3 Solid Waste Disposal Impact

None of the regulatory options being considered generates solid waste. Consequently, discussion of solid waste disposal impacts is not applicable to this analysis.

3.5.4 Energy Impact

Table 3-3 presents the total energy requirements for each regulatory option as applied to the 300,000 Mg/yr uncontrolled model plant. Energy requirements for Regulatory Options 1, 2, and 3 amount to less than

TABLE 3-1. STACK SOURCE CHARACTERISTICS FOR EXCESS EMISSIONS

Scenario	Source	Annual Average Emission Rate (G per sec)	Height (meters)	Temp. (Deg.K)	Exit Vel. (m/sec)	Diameter (meters)
Uncontrolled Model Plant[b]	Process Vents:[a]					
	Atmospheric Pressure Columns	0.063	12	318	0.1	0.33
		0.063	12	318	0.1	0.33
	Alkylation Reaction Vents	0.063	12	318	4.9	0.06
		0.063	12	318	4.9	0.06
	Benzene/Toluene Column	0.063	12	318	0.1	0.23
	Vacuum Columns	0.063	12	318	0.1	0.11
		0.063	12	318	0.1	0.11
		0.063	12	318	0.1	0.11
	Hydrogen separation vent compressor failure-uncontrolled	0.272	6	318	19.8	0.50
Regulatory Option 1 -- Recycle[b]	H_2 Section-Flare -startup	0.010				
	H_2 Section-Flare -outage	0.051				
	Process Vents-Flare	0.006				
Regulatory Option 2 -- Dual Compressor[b]	H_2 Section-Flare -startup	0.010	90	823	0.1	13.7
	H_2 Section-Flare -outage	0.005				
	Process Vents-Flare	0.006				
Regulatory Option 3 -- No Excess Emissions[b]	All vents to flare	0.003				

[a] The atmospheric pressure columns discharge horizontally and the benzene/toluene and vacuum columns discharge downward. Values given are the modeling inputs for these sources, after adjustments, as discussed in the text of the main BID. The actual stack height and diameter for these sources are 12.0 and 0.06 m, respectively.

[b] Values given are the modeling for the flares, after adjustments, as discussed in the main text. Actual characteristics for the flares are:
3-inch flare: height = 20m, diameter = 0.1m, flow rate = $0.05 m^3$/sec.
H_2 flare: height = 60m, diameter = 0.3m, flow rate = $3.89 m^3$/sec.

TABLE 3-2. MAXIMUM ANNUAL AVERAGE BENZENE CONCENTRATIONS FOR THE FOUR EXCESS EMISSIONS REGULATORY OPTIONS

Scenario[a]	Maximum Concentration At Any Distance (ppb)	Distance to Maximum Concentration (km)
Uncontrolled Plant	7.9	0.16
Regulatory Option 1 -- Recycle/Flare	4.3×10^{-3}	2.0
Regulatory Option 2 -- Recycle/Flare/ Dual Compressor	1.4×10^{-3}	2.0
Regulatory Option 3 -- Boiler/Flare	2.0×10^{-4}	2.0

[a] The maximum annual average concentrations under each scenario are from the Dow, Texas, EB/S plant.

TABLE 3-3. TOTAL ENERGY REQUIREMENTS OF REGULATORY OPTIONS FOR EXCESS EMISSIONS

(300,000 Mg/yr Uncontrolled Model Plant)

Total Process Energy Requirements for the Model Plant MJ/yr (bbl/yr)[a]	Option 1 Recycle/ Flare MJ/yr (bbl/yr)	Option 2 Recycle/Flare/ Dual Compressor MJ/yr (bbl/yr)	Option 3 Boiler/ Flare MJ/yr (bbl/yr)
6.9×10^9	$5,230 \times 10^3$	$5,100 \times 10^3$	$5,100 \times 10^3$
(1.1×10^6)	(840)	(820)	(820)

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[a] Barrels of oil equivalent, assuming 140×10^3 Btu/gal.

0.1 percent of total plant energy requirements. All energy impacts are essentially linear with respect to plant capacity.

3.5.4.1 Regulatory Option 1

The smokeless flare requires energy in the form of steam for smokeless operation and natural gas both for pilot operation and purge requirements. Total energy for these requirements is approximately 5.23 x 10^6 MJ/yr for the model plant. In terms of nationwide impacts, Regulatory Option 1 would require 71 x 10^6 MJ/yr.

3.5.4.2 Regulatory Option 2

Energy requirements for the smokeless flare under this option are nearly the same as those for Regulatory Option 1 except that slightly less steam is required for the projected three hours of flare operation. Energy needs for steam and natural gas are approximately 5.14 x 10^6 MJ/yr. The backup compressor has no incremental energy impact since only one compressor will be in use at a given time. In terms of nationwide impacts, Regulatory Option 2 would require approximately 70 x 10^6 MJ/yr.

3.5.4.3 Regulatory Option 3

Regulatory Option 3 requires that all safety valves used in relieving surges in process streams be manifolded to a ten-inch smokeless flare. Energy requirements for the flare under this option are nearly the same as those for Regulatory Option 2 except that even less steam is required for the projected 15 minutes of flare operation. Energy requirements for steam and natural gas are 5.1 x 10^6 MJ/yr. The nationwide energy requirement for this option would be 69 x 10^6 MJ/yr of energy or approximately 11,200 bbl/yr (fuel oil equivalent) for all existing EB/S plants.

Regulatory Option 3 also requires that an existing EB/S boiler be retrofitted to accept vent streams generated as a result of plant startup/shutdown and malfunction. Energy requirements for the boiler are negligible as are credits in terms of steam generated as a result of combusting the waste stream.

3.5.5 Other Environmental Concerns

3.5.5.1 Flare Noise and Thermal Radiation

The flaring process and the noise it generates may have an impact on the surrounding environment. Estimated sound pressure levels (decibels (dB)) of the ten-inch flare are approximately 84 dB at the base of the flare stack. This estimate assumes no steam injection. While the introduction of steam into the combustion zone of the stack increases its destruction efficiency, it may increase overall noise levels of the flare.[2] However, it is believed that flares can be designed properly to minimize noise. Table 3-4 compares flare noise levels with OSHA standards and EPA recommendations for noise levels requisite to protect public health and welfare in the industrial environment.[3,4]

Sound pressure levels are reduced as a function of distance.[5] Sound pressure levels of the ten-inch flare require a distance of 340 meters to fall to 70 dB.*

Flares also emit thermal radiation.[6] Stack height is determined so that personnel working in the vicinity of the flare are exposed to only harmless levels of thermal radiation. Though the thermal radiation of the ten-inch flare is greater than that of the process flare, stack height of the larger-diameter flare is correspondingly greater.

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*EPA recommendations for maximum dB level to protect against hearing loss (24-hour exposure).

3.6 COST IMPACT

Table 3-5 presents a summary of installed capital costs for specific equipment, used alone or in combination, for control of benzene emissions due to EB/S plant startup, shutdown, and equipment malfunction. Actual costs will vary somewhat depending on plant capacity and existing controls; those presented are based on the 300,000 Mg/yr uncontrolled model plant.

Though neither recovery nor energy credits is possible with the smokeless flare, both the boiler and the backup compressor recover some of the benzene or heat value of the waste streams. The backup hydrogen separation compressor can be on line within one hour of a primary compressor malfunction. Assuming an outage duration of ten hours per year, the backup compressor can continue to control the hydrogen separation stream, thereby providing benzene recovery and utilization of the remaining hydrogen-rich stream as supplemental fuel in the steam superheater.

Table 3-6 presents the industry-wide economic impact and annualized costs per regulatory option. Regulatory Option 1 requires the least capital outlay of approximately $524,000 for the purchase and installation of flares at four of the 13 plants. Regulatory Option 2 would require a capital outlay of approximately $5.5 million for the purchase and installation of flares or backup compressors at six plants. Regulatory Option 3 would require the greatest capital outlay of approximately $20.0 million for flares or a boiler retrofit and controls at 13 plants. Industry-wide annualized costs for Regulatory Options 1, 2, and 3 would be $171,000, $1.6 million, and $5.2 million, respectively.

TABLE 3-4. FLARE NOISE LEVELS RELATIVE TO OSHA STANDARDS AND EPA GUIDELINES

Estimated Flare Noise (dB)	Comparative Noise Levels (dB)	
10" Flare	EPA Guideline for Industrial Area[a] (Hearing Loss Consideration for 24-Hour Levels)	OSHA Permissible Noise Exposure[b] (8-Hour Exposure Level)
84	70	90

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[a] Sound levels identified as requisite to protect the public health and welfare with an adequate margin of safety.

[b] Sound level dBA slow response.

TABLE 3-5. CONTROL EQUIPMENT COSTS[a]
(in thousands of dollars)

Control Equipment	Total Installed Capital Costs
Ten-inch flare, header, and all necessary control equipment	$131.0
Backup H_2 separation compressor and controls	828.0
Existing boiler retrofit and controls	1,518.0

[a] Based on the 300,000 Mg/yr model plant.

TABLE 3-6. CAPITAL AND ANNUALIZED COSTS TO EB/S PER REGULATORY OPTION[a]

(thousands of dollars)

Option	Capital Costs	Annualized Costs	No. of Plants
Regulatory Option 1 (Flare)	\$524	\$ 171	4
Regulatory Option 2 (Dual Compressor/ flare)	\$5.5	\$1,600	6
Regulatory Option 3 (Boiler/flare)	$\$20.0 \times 10^3$	\$5,200	13

[a] Represents costs to indicated number of plants lacking equipment required by regulatory option.

Regulatory Option 4 would have the most severe economic impact on the EB/S industry. Because 100 percent control of excess emissions is technically infeasible, the industry would either be in noncompliance or be forced to close. This impact is discussed in detail in Chapter 7 of the BID.

3.7 REFERENCES

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5. Swithenbank, J. Ecological Aspects of Combustion Devices With Reference to Hydrocarbon Flaring. Department of Chemical Engineering and Fuel Technology, University of Sheffield, Sheffield, England. p. 553. May 1972.

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4. ETHYLBENZENE AIR OXIDATION ANALYSIS

4.1 INTRODUCTION

In the existing ethylbenzene/styrene (EB/S) facilities being analyzed for regulation, most benzene-containing process vent streams are similar in composition and therefore can be controlled by the basic control techniques described in Chapter 4. However, in the production of styrene from ethylbenzene hydroperoxide, the oxidation of ethylbenzene with air to produce ethylbenzene hydroperoxide results in a benzene-containing vent stream with a markedly different composition. Because of this significant difference in composition, the vent is analyzed separately.

4.2 EMISSIONS

The ethylbenzene oxidation reactor vent releases nitrogen and excess oxygen brought into the process with the reaction air; carbon monoxide, carbon dioxide, and light organics produced in the reaction; and organics entrained in the vent gas. The vent stream has a reported flow of approximately 16.4 cubic meters per second (m^3/sec) (580 cubic feet per second (ft^3/sec)) and contains approximately 4.4 percent by weight aromatics, or 3,400 kilograms per hour (kg/hr) (7,480 pounds per hour (lbs/hr)).

At the Oxirane facility, the only U.S. plant using ethylbenzene hydroperoxidation, the vent gas is scrubbed with oil and water for 99 percent removal of organics as required by process economics. The resulting stream is vented to the air and contains 35 parts per million (ppm) benzene or 7.2 kg/hr.[1]

Since a high flow stream dilute in organics cannot be effectively controlled by boilers, condensers, or scrubbers, an alternate control technique must be examined.

4.3 CONTROL TECHNIQUES

The prospects for new plants using the ethylbenzene hydroperoxidation process depend almost exclusively on market dynamics. The supply of propylene oxide is governed by only five producers nationwide. Given the concentrated nature of the existing market for propylene oxide and the prediction of excess capacity in both styrene and propylene oxide in the near future, it is unlikely that a new producer would enter either market. Oxirane already had been marketing propylene oxide from a different production facility when it constructed its coproduct plant. In this way, production efficiency for propylene oxide was enhanced without creating a surplus in supply. Coproducing styrene served to ease a market supply deficit in styrene at competitive prices. Therefore, the control technique analysis for the ethylbenzene air oxidation vent need focus only on the existing facility.

Thermal oxidizers are the most widely employed method to control volatile organic compounds (VOC) emissions in dilute streams. Thermal oxidizers destroy VOC through oxidation to carbon dioxide and water. Temperatures of 1,300 to 1,600°F are sufficient to nearly complete conversion of most substances in 0.1 to 0.75 seconds residence time. Destruction of most hydrocarbons occurs rapidly at 1,100 to 1,200°F, but oxidation of carbon monoxide to carbon dioxide requires the higher temperatures and residence time.[2]

A thermal oxidizer system consists of a combustion chamber, a heat recovery unit, and an exhaust system consisting of blower, fan, ductwork, and a stack. The combustion chamber can be of any shape or cross-section, although a cylindrical chamber generally is preferred. It can be either horizontally or vertically disposed, having a burner located so that it is able to heat the incoming offgas stream to the desired temperature before it exits the oxidizer chamber.

Burner type and arrangement affect combustion rates and residence time. The more thorough the contact of flame with the waste organics, the shorter the time required for complete combustion. Burner placement depends not only on the burner type, but also on the design requirement for intimate contact of the combustible gases with the burner flame. Maximum efficiency occurs when all of the combustible matter passes through the burner. Multi-jet and mixing-plate burners provide the most effective flame contact.[3] The oxidizer may be refractory-lined or it may be constructed of heat resistant metal, depending upon the destruction temperature selected for the organic waste gas.

Thermal oxidizers discharge flue gases at a temperature of 1,300 to 1,500°F. This generally would represent inefficient use of energy if not recovered. Recovery methods include heat exchange between hot flue gases and incoming cool offgas stream, recycling a fraction of the hot flue gases to the process, and the use of the heat in other processing or heating loads, such as in generating steam for plant or process heating, or power generation.

Combustion temperature determines whether recuperative heating or waste heat boilers apply in recovering a portion of the waste heat. Combustion temperatures exceeding 1,600°F rule out the use of recuperative heat exchangers because of construction materials problems as well as secondary factors such as pre-combustion occurring in the exchangers. However, waste heat boilers are alternatives in this range. Temperatures of less than 1,500°F are compatible with standard recuperative heater designs and waste heat boilers may be considered throughout this range.

VOC destruction efficiency will increase with increasing concentration of VOC in the offgas stream. This is partly due to the first order dependence of oxidation rates on VOC concentration and partly due to the significant local heat of reaction which is released during oxidation. It is estimated that at incinerator temperatures of 1,600°F and residence times of 0.75 seconds, a minimum of 70 percent destruction efficiency for a 35 ppm benzene stream can be achieved.

4.4 REGULATORY OPTIONS

Based on the use of a thermal incinerator as the control technique, two regulatory options are being considered for benzene emissions from the ethylbenzene air oxidation vent:

- Require that the facilities producing styrene from ethylbenzene hydroperoxide reduce benzene emissions to a maximum of five ppm. This alternative is based on the use of an incinerator operating at a temperature of 1,600°F and a 0.75 second residence time.
- Do not regulate facilities producing styrene from ethylbenzene hydroperoxide.

4.5 ENVIRONMENTAL AND ENERGY IMPACTS

Depending on the type of incinerator chosen, energy requirements are 1.3×10^9 MJ/yr for the unit with no heat recovery, 3.2×10^8 MJ/yr for that with 70 percent heat recovery, and 5.1×10^8 MJ/yr net energy requirement for a waste heat boiler. Expressed as a unit of energy per megagram of benzene destroyed, the energy requirement for the incinerator with no heat recovery is approximately 4.3 x 10^7 megajoules per megagram (MJ/Mg); for the 70 percent heat recovery scenario, the energy requirement is 1.0 x 10^7 MJ/Mg. The waste heat boiler would require approximately 1.6 x 10^7 MJ/Mg. Comparing this energy requirement to that of the other process vent streams, Regulatory Option C would provide an energy credit of 53 x 10^6 MJ/yr.

4.6 SECONDARY ENVIRONMENTAL IMPACTS

Table 4-1 illustrates the typical stack constituents of a thermal oxidizer unit. Relative stack gas makeup should remain constant whether or not a heat exchanger is used.

4.7 COST ANALYSIS[4]

Calculations of incinerator costs for the ethylbenzene air oxidation vent are based on the following production levels and stream characteristics: (1) 635,000 Mg/yr total production, 454,000 Mg/yr of styrene monomer, 181,000 Mg/yr of propylene oxide; (2) a stream flow rate of 35,000 standard cubic feet per minute (scfm); (3) a stream thermal content of 1 Btu/scf; and (4) a stream composition of 95.6 percent inerts.

As presented in Table 4-2, capital costs for the three control configurations are $1,354,000, $2,554,000, and $2,240,000 for the no-heat-recovery incinerator, the 70 percent heat recovery incinerator, and the waste heat boiler, respectively. Annualized costs for the same configuration are $3,461,000, $1,448,000, and $1,756,000, respectively. Cost-effectiveness for each scenario is $86,000/Mg for no heat recovery, $36,000/Mg for 70 percent heat recovery, and $44,000/Mg for a waste heat boiler.

TABLE 4-1. TYPICAL OUTPUT OF THERMAL OXIDIZER[5]

Component	Composition (Volume Percent)	Emission Ratio (lbs. per thousand scf waste gas)
CO_2	4	2.2
H_2O	10	12.2
N_2	82.9	65.1
O_2	3	2.1
VOC to Methane	500-50 ppm	0.0022-0.0002
CO	10-6 ppm	0.001-0.0005
Particulates	30-3 ppm	0.001-0.0001
SO_2	1 ppm	0.00005-0.00001
NO_x	160-30 ppm	0.02-0.004

TABLE 4-2. ALTERNATIVE HEAT RECOVERY SCENARIOS AND COSTS
(thousands of dollars)

Incinerator Type	Capital Cost	Annualized Capital Cost	Utility Cost	Labor	Annualized Cost	Cost-Effectiveness
No Heat Recovery	1,354	393	3,050	18	3,461	86/Mg
70% Heat Recovery	2,554	741	675	32	1,448	36/Mg
Waste Heat Boiler	2,240	650	3,050 [1,980][a]	36	1,736	44/Mg

[a] Value of recovered steam.

4.8 REFERENCES

1. Letter from Fretwell, S., Oxirane to Farmer, J., EPA. November 19, 1979. Concerning ethylbenzene air oxidation process.

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3. Control Techniques for Volatile Emissions from Stationary Sources. EPA-450/2-78-022. May 1978.

4. Letter from Towell, T.W., Halcon to Peterson, C., Hydroscience. March 22, 1979.

5. Blackburn, J. W. Emission Control Options for the Synthetic Organic Chemical Manufacturing Industry. Control Device Evaluation: Thermal Oxidation. EPA Contract No. 68-02-2577. Hydroscience, Inc. December 1979.